GREENING THE CHEMISTRY CURRICULUM

A. N. RIDLEY

MPhil

2011

GREENING THE CHEMISTRY CURRICULUM

To embed the concepts of sustainability and environmental responsibility into the chemistry curriculum in order to equip graduates for future practises in the chemical sciences

Amy Nicola RIDLEY

Submitted for the degree of Master of Philosophy

Department of Chemical and Forensic Science

University of Bradford

2011

Amy Ridley: Greening the Chemistry Curriculum

Keywords: Sustainability, Chemistry Curriculum Metrics, Green Chemistry, Environmental Awareness

Sustainability and environmental responsibility is increasingly growing in importance. Solving the environmental problems of the planet will one day become the responsibility of future scientists. For this reason, and with the introduction of new chemical legislation (REACH) driving change it is essential that current students are given a broad introduction to sustainability and environmental responsibility in order to equip them as graduates for future practice in the chemical sciences. At the University of Bradford the aim is to teach sustainability and environmental responsibility by embedding it throughout the entire chemistry curriculum rather than teaching it in standalone lectures. Once this has been established within chemistry it is expected that this will potentially provide a template for other areas of laboratory science within the university.

In order to achieve the aim of this project, students, staff and potential employers took part in surveys with a view to inform curriculum development. Examples of best practice were sought and used as guidance for the development of directed learning activities for use as post lab questions and utilisation of the twelve principles of green chemistry.

Green chemistry metrics were applied to undergraduate experiments to test how well they would work in terms of ease of use, applicability and judging ‘greenness’. It was found that these were not very effective for use within an undergraduate laboratory due to applicability and judging ‘greenness’, however this work highlighted other areas for

improvement. As a result of this work an environmental assessment metric system was developed for use within an undergraduate setting.

Contents

CHAPTER ONE: Introduction

1.0 Aims and Objectives 1

1.1 Introduction to the need for sustainable practice 2

1.2 The Concept of Sustainability 2

1.3 Sustainable Development and Green Chemistry 3

1.4 Drivers for Sustainability and Green Chemistry 4

1.4.1 Poor public image of the chemical industry and concern for the environment........ 4

1.4.2 Chemical legislation 6

1.4.2.1 The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) 6

1.4.2.2 The Restriction of the Use of Certain Chemicals (RoHS) 8

1.4.3 Student numbers 8

1.4.4 Economic drivers 9

1.5 Green Chemistry Education 10

1.5.1 Content 11

1.5.2 Approaches for integration 12

1.5.2.1 Using the Principles of Green Chemistry to enhance the curriculum 12

1.5.2.2 The use of green chemistry textbooks 14

1.5.2.3 Laboratory classes 14

1.5.2.3.1 Alternative experiments 14

1.5.2.3.2 Raising awareness of the dangers of chemicals 15

1.5.2.3.3 The use of metrics and Pre and Post Lab Questions 15

1.5.2.3.4 Waste monitoring 16

1.5.2.3.5 Microscale Chemistry 16

1.6 Case Examples of Best Practise and Existing Chemistry Curricula 18

1.6.1 labRATS at the University of California: Santa Barbara........ 18

1.6.2 Existing Chemistry Curricula 19

1.6.2.1 General Green Chemistry Modules 19

1.6.2.2 Green chemistry and sustainability and specific topics 21
1.6.2.3 Degree courses 21
1.6.2.4 Green chemistry embedded into the curriculum 22
1.7 Potential barriers to the inclusion of sustainable development within education 23
1.8 Summary 24

CHAPTER TWO: Student Perceptions of Green Chemistry and Sustainability

2.0 Introduction to using qualitative research within Chemistry 26
2.1 Aims of this part of the study 26
2.2 Data Collection Plan 27
2.2.1 Groups 27
2.3 Methods of data collection 28
2.3.1 Observation 28
2.3.1.1 The use of observation in this study 30
2.3.1.2 Documenting field notes 33
2.3.2 Questionnaires 34
2.3.2.1 The use of questionnaires in this study 34
2.3.3 Questionnaire development 36
2.4 Reflections on data collection 38
2.4.1 Observation 38
2.4.1.1 MSc Analytical Sciences Group 38
2.4.1.2 First Year Chemistry Students Group 39
2.4.2 Questionnaires 40
2.4.2.1 Pilot questionnaire and modifications 40
2.4.2.2 Response rates 42
2.4.2.3 The amount of data (Observation and Questionnaire methods) 44
2.5 Results and Analysis 46
2.5.1 Observation Field Notes 46

2.5.1.1 MSc Analytical Sciences Students 46

2.5.1.2 Findings 47

2.5.1.3 First Year Chemistry Students 57

2.5.1.4 Findings 57

2.5.2 Analysis of Questionnaires 72

2.5.2.1 MSc Analytical Sciences Students 72

2.5.2.2 Findings 73

2.5.2.3 First Year Chemistry Students 90

2.5.2.4 Findings 91

2.5.3 Summary of findings of student perception study 111

CHAPTER THREE: Potential Future Employer and Staff Perceptions of Environmental Awareness and Sustainability in the Curriculum

3.0 Introduction 114

3.1 Introduction to employer perception study 114

3.2 Aims of potential future employer study 115

3.3 Data Collection Plan 116

3.3.1 Method of data collection for staff and company perceptions 116

3.3.1.1 Telephone surveys and interviewing as a data collection method 117

3.3.2 Participants of the employer perception study 121

3.3.3 Response rates: employer study 121

3.4 Findings of the employer perception study 122

3.5 Introduction to staff perception of the introduction of environmental awareness and sustainability into the chemistry curriculum 132

3.6 Aims of staff perception study 133

3.7 Data Collection Plan 134

3.7.1 Data Collection 134

3.7.2 Participants of the study 134
3.7.3 Response rates 134
3.8 Findings of staff perception study 135
3.9 Summary of findings of staff and employer perceptions........ 142

CHAPTER FOUR: Green Chemistry Metrics

4.0 Introduction 143
4.1 Review of Green Chemistry Metrics 144
4.1.1 Yield 145
4.1.2 Atom Economy........ 146
4.1.3 Environmental (E) Factor 148
4.1.4 Effective Mass Yield (EMY)........ 152
4.1.5 Mass Intensity........ 154
4.1.6 Reaction mass efficiency (RME)........ 155
4.1.7 Carbon Efficiency........ 156
4.1.8 The EcoScale 156
4.1.9 Summary of literature review 158
4.2 Experimental 162
4.2.1 Results 164
4.2.2 Discussion 167
4.2.3 Summary of findings 194
4.2.3.1 Waste 194
4.2.3.2 Scale 194
4.2.3.3 Applicability 195
4.2.3.4 Ease of applying within an undergraduate laboratory environment........ 198
4.2.3.5 Judging ‘greenness’ 199
4.2.3.6 Summary........ 200
4.3 Developing a metric system 201

4.3.1 Criteria for the metric system ... 203

4.3.1.1 Reaction efficiency ... 207

4.3.1.2 Reaction Waste ... 209

4.3.1.3 Toxicology and Safety ... 210

4.3.1.4 Energy Consumption ... 212

4.3.1.5 Resource Consumption ... 213

4.3.2 Adapting the metric system ... 214

4.3.3 Testing the metric system ... 215

4.3.4 Summary of metric system ... 220

CHAPTER FIVE: Conclusions

5.0 Conclusions and further work ... 222

6.0 References ... 224

Acknowledgements

A big thank you to my supervisors Dr Beverley Lucas, Dr Tasnim Munshi and Dr Ian Scowen for their help and guidance throughout this year.

Thank you to Ecoversity at the University of Bradford for funding this project, and the students, staff and companies that participated in the studies.

Finally, a huge thank you to all my family and friends for their support throughout my MPhil.

CHAPTER ONE: Introduction

1.0 Aims and Objectives

This project aims to provide a starting point in to embedding the concepts of sustainability and environmental responsibility into the chemistry curriculum at Bradford. This is in order to equip graduates for future practise in the chemical sciences. To achieve this, the following objectives were established:

- A review of current practise in taught chemistry programmes and best practice to determine the best way of integrating sustainability and environmental awareness
- Needs analysis: exploring the perceptions that staff, students and potential future employers have of sustainability and environmental awareness in order to inform curriculum development
- Testing of green chemistry metric systems which provide a quantitative way of measuring the environmental impact of chemical reactions, to establish how well they can be applied to undergraduate practicals in terms of ease of use and applicability and to use them to identify areas for improvement such as reducing scale of reaction and waste generation
- The development of an environmental assessment metric system prototype which incorporates areas of practical chemistry which may not necessarily be addressed by green chemistry metrics

1.1 Introduction to the need for sustainable practice

Over the past decade, many literature articles and conferences have focused on the subject of lessening negative human impacts on the planet and on its ability to sustain life. A number of issues have been raised through these discussions and from these; specific goals have emerged such as increasing recycling, minimising waste and reaching sustainability. These goals can help to provide a focus of what needs to be achieved in order to lessen impacts. Currently approaches are being established throughout disciplines, industries and sectors in order to achieve these goals. [1]

1.2 The Concept of Sustainability

Sustainable development has been named as one of the biggest challenges of the 21st century. [2] The World Commission on Environment and Development (WCED) were the first to define the concept of sustainability in 1987 as 'Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' [3] It is also described by the 'three pillars of sustainability' (or three stools) also known as, 'the triple bottom line concept.' [3] The Brudtland commission presented a 'two-pillar' model outlining the concerns of environment and development [4, 5] this was further extended to the three pillar model, which separates the development issues into economical and social aspects. The three pillars of sustainability are presented as environmental, social and economical considerations but the order in which different groups and analysts view them varies.

Sustainable development is gaining more interest as a concept and it is now accepted by governments, industry and the public as a necessary goal for achieving the desired combination of ecological, economical and societal objectives. [6] It aims for equity between different parts of the world and between generations. Although the objectives of sustainable development can be stated clearly, the route to sustainability is less clear and much more difficult. [7]

1.3 Sustainable Development and Green Chemistry

It has been reported by Anastas that over the past 200 years, Chemistry has followed a path of creativity, innovation and discovery with little or no consideration of the potential impact on the environment that the created methods and processes are having. [8] This is partly due to a lack of understanding and knowledge of the hazards associated with chemicals in terms of their impact on human health and the environment. However, as the sciences have developed so has the understanding of the adverse effects of chemicals. This has also led to a better understanding at molecular level allowing chemical processes and products to be designed in such a way that reduces the adverse effects of the chemistry being carried out. [8] It must also be noted that the mass media may have influenced Anastas as they are often keen to focus on the negative side of the industry and forget the good that it brings to society.

Green Chemistry, also known as Sustainable Chemistry, is a philosophy related to the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. [6] Green Chemistry represents two components; efficient utilisation of raw materials and the elimination of waste, and health, safety and environmental features of chemicals and their manufacturing processes. [9] It has been accepted that green chemistry is the way to allow chemists to design a safer, healthier and more sustainable world. [8]

The Green Chemistry movement began in the early 1990's in the United States of America by the Environmental Protection Agency (EPA) as a means of encouraging industry and academia to use Chemistry for pollution prevention. [6] Following the Green Chemistry programmes in the US, it was later introduced in both the United Kingdom and Italy. [10] It has since evolved from its roots in academic research to become a mainstream practise supported by academia, industry and the government. [11] To aid the efforts to introduce the subject, the American Chemical Society (ACS) and the Environmental Protection Agency (EPA) developed the Twelve Principles of Green Chemistry as a way of guiding the practise of Chemistry in a responsible manner. [12, 13]

1.4 Drivers for Sustainability and Green Chemistry

Clark has presented a number of drivers for change, falling into the three areas of sustainability- economical, environmental and societal. [14] The chemical industry has suffered a poor public image in recent years, and is more notorious for headlines relating to environmental disaster and accidents rather than the benefits and innovation that chemistry brings to society. [15, 16] Along with this is also the recent introduction of legislation which has led to an increase in pressure on the chemical industry to make changes for the better. Clark has commented how this negative outlook on the chemical industry has been partly blamed for apparent falling numbers of students studying chemistry at undergraduate level. [14] The following sections expand on these areas.

1.4.1 Poor public image of the chemical industry and concern for the environment

As already mentioned, in recent years the chemical industry has neglected its image and reputation and disowned what it failed to control. A survey commissioned by the UK's

Chemical Industries Association (CIA) discovered that the public opinion of the chemical industry is improving; however in the report for 2007 it had only reached 26 % approval. [16] Cefic (The European Chemical Industry Council) have reported that in contrast to this was the higher public approval of the plastics and pharmaceutical industries, this is thought to be a result of the visible benefits of the products that they produce. [17, 18]

It is now being realised that the public recognise the social and economic costs of cleaning up pollution from the air and water, and of preserving outdoor spaces. This initial rise of concern is thought by Downs to be the result of recent deterioration of noticeable environmental conditions including oil spills, urban smog, pollution of water by chemicals and the threatened disappearance of many forms of wildlife. [19] Other reasons for the negative opinions of the chemical industry mentioned by Clark [18] are transport, safety and waste. The millions of people observing these conditions believe that someone should do something about them. [19]

Although the general public see the chemical industry as having a negative impact on the environment and public safety, it is in fact one of the most successful of the manufacturing industries; encountering huge economic success and benefiting everyday lives with the large assortment of products that it provides societies with. Clark comments how this success must be matched in terms of environmental performance to ensure that the public do not perceive this industry as being ‘necessary evil’. [18] It has been reported that the public generally have different ideas about sustainability, however Roon *et al*. comment that it is generally accepted that the chemical industry must be redesigned to guide it towards a more sustainable direction. [20] Cognis (a personal care chemical supplier) have also commented that consumers are also more inclined to buy products that combine sustainability and wellness benefits. [21]

1.4.2 Chemical legislation

In the past two and a half decades legislation has played a key role in the chemical industry. Many developed countries have introduced environmental and chemical legislation as a means of regulating the chemical industry. This has mostly been encouraged and guided by the Organisation for Economic Co-operation and Development (OECD) which has also produced guidelines for safer industrial activities and processes. [22]

According to Clark, [14] the introduction of REACH- the Registration, Evaluation, Authorisation and Restriction of Chemicals [23] is probably one of the most important chemical legislations ever seen. Along with this is the introduction of the Restriction of Hazardous Substances (RoHS). Although some view legislation negatively, it has been seen as an effective way of improving the environment. [22]

1.4.2.1 The Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

Sustainable Chemistry has advanced significantly after the introduction of legislation such as REACH- the Registration, Evaluation, Authorisation and restriction of Chemicals [10]. It came into force within the European Union on 1st June 2007 and replaced a number European directives and regulations with one single system. REACH is precaution based rather than a sole reliance on risk assessment and shifts the regulatory responsibility of the government agencies to the companies to show that their chemicals are safe for use. This legislation provides a major shift towards green chemistry and ensures that it will not be regarded as a 'fad' and will be here to stay. [24]

REACH has several aims, including [23] :

- Providing a high level of protection of both human health and the environment from the use of chemicals.
- To make manufacturers and importers of chemicals placed on the market responsible for understanding and managing the risks associated with their use.
- To allow the free movement of substances on the EU market.
- To enhance innovation and the competitiveness of the EU chemicals industry.
- To promote the use of alternative methods for the assessment of the hazardous properties of substances e.g. quantitative structure-activity relationships (QSAR) and read across.

As part of the legislation, REACH requires the authorisation of chemicals. At this stage the agency is responsible for authorising what can be used and where. The most difficult to authorise will include those chemicals which are suspected to be carcinogenic, mutagenic or toxic, and those that are bio accumulative and persist in the environment. In 2009 these chemicals began to be placed on a candidate list, a number of these chemicals with alternatives will be phased out, and those without alternatives but considered dangerous will be used under certain regulatory conditions. This list is reassessed periodically (every five years), with new chemicals added and to see whether there are new alternatives to those on the list. This could mean that chemicals used within Chemistry in education, industry and manufacture could be restricted for use and a shift in practise will be required. Chemical suppliers will also encounter pressure on them to provide alternatives to those on the candidate list. [23]

1.4.2.2 The Restriction of the Use of Certain Chemicals (RoHS)

RoHS, the Restriction of the Use of Certain Hazardous Substances is a regulation that came into force within the UK on 1st July 2006. The National Measurement Office (NMO) works in partnership with the policy lead at the Department for Business, Innovation and Skills (BIS) for these restrictions. The regulations implement EU directive 2002/95 which prohibits new electrical and electronic equipment containing lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) over the agreed levels. Companies and manufacturers must understand these requirements to ensure that their components and products comply. [25] This legislation has resulted in a shift in practise of some companies in order to comply with these regulations, meaning products have had to be redeveloped in order to fulfil the requirement. This has also led to companies advertising their RoHS compliant products in an attempt to promote a greener product to secure a market place. [14]

1.4.3 Student numbers

Statistics provided by the Royal Society of Chemistry [26] relating to UCAS applicants for courses within chemistry show a decline in the number of applicants between 1996 and 2007 by 8.2%. Clark has considered the reasons for this reduction in student application numbers and believes that the negative press that the chemical industry often receives is deterring students from applying for such courses. As a result of this, if more students are going to be attracted then the subject image must also be changed. Clark has also commented on how young people tend to be interested in environmental issues and if chemistry can be viewed as a subject playing a vital role in understanding the environment, and improving it by managing it better whilst still providing the products essential to the lifestyles that we are now accustomed to, it may attract more students. [15] This provides a great opportunity for universities to introduce green chemistry to benefit the students in terms of a better education, and the university and environment, by producing chemists aware of these issues and with knowledge that changes current practise.

1.4.4 Economic drivers

Rising costs within the chemical industry such as increase in the cost of raw materials, waste disposal, loss in efficiency and fines for pollution are also driving the movement towards sustainability. Companies within the industry are facing a challenge whereby they must develop new products, services and processes that are in agreement with the three pillars of sustainability. This should minimise the raw materials and energy needed for these processes and attempt to reduce or even better, eliminate the production of waste that can often end up in the environment, reducing this should in turn reduce costs. In 2007, the UK alone produced 8.45 Megatons of hazardous waste. [27] Many companies are now coming to realise that Green Chemistry will benefit them in terms of financial advantages by the use of shorter processes, higher efficiency and less waste for disposal. [8]

Although most of these drivers are associated with negative connotations, they show the need for a shift in current practise within the chemical industry and hence provide a great opportunity for innovation into green chemistry through education, research and the industry itself. This should position chemists to lead the way to a sustainable future and to potentially start to undo the years of neglect that the chemical industry has inflicted on the environment.

1.5 Green Chemistry Education

Integration of Green Chemistry education at the undergraduate level is said to be key to adopting more sustainable practices and therefore a more sustainable society. [8, 11] Students can benefit from this education as they can learn the importance of sustainable practice, become aware of positive everyday habits and learn that although the chemical industry has contributed largely to environmental degradation, that it is also a solution to the environmental problems currently seen. [8]

As green chemistry has become more accepted, courses have been developed throughout various institutions, mostly at undergraduate level. Although greening of chemistry curricula has begun, so far the implementation of green chemistry has not been uniform with the most attention being given to organic chemistry. Some have argued that the twelve principles of green chemistry are only applicable in this area due to the focus on synthesis; however, they provide a great starting and focal point to drive the green chemistry curriculum development further. [8]

There have been a number of papers published that emphasise how important the implementation of green chemistry and sustainability are within the chemistry curriculum. Braun *et al*. have stated that this implementation is not just desirable but it is necessary. [12] It has been established that the best way to green the chemistry curriculum is to integrate the concepts into the existing one rather than adding to an already crowded curriculum. [8, 12] It has also been noted that students should be introduced to the concepts as early on in their educational careers as possible. [12] The following describes approaches suggested for the implementation of green chemistry with references to approaches taken and examples of best practise within these areas.

1.5.1 Content of the Curriculum

In 2006 Braun *et al*. published what they believe should be contained chemistry in terms of greening the curriculum. [12] The following table summarises some of the concepts that are considered by them as the most important ones for students to understand.

General Concepts	Students should; Realise that current processes are not perfect and the constant drive for improvement will lead to a more sustainable future. Understand what is considered to be sustainable, renewable and environmentally benign for those designing reactions and processes. Possess an understanding of the dangers associated with chemicals.
Chemistry	Attempt to use environmentally benign chemicals as it is not always possible to track the fate of every chemical compound used. Evaluate reactions on efficiency, sustainability, recyclability and elimination or reduction of hazard as well as the traditional conversion and selectivity. Understand the connection between chemical structure and compound activity (e.g. hydrophobicity/licity, sterics and toxicity) this can provide a basic understanding of how chemicals impact the environment.
Global Issues	Have an awareness of globalisation and how it must be environmentally responsible.

Table 1.1 Proposed content for greening the chemistry curriculum by Braun *et al*. [12]

These concepts are not designed to replace existing material, but to enable classes to be taught in a new way. The concepts should not be taught as a separate section but embedded into the current material.

1.5.2 Approaches for integration

One of the main concerns with educators is how to implement green chemistry into an already crowded curriculum, the following show examples of approaches suggested and adopted by the green chemistry community and institutions around the world.

1.5.2.1 Using the Principles of Green Chemistry to enhance the curriculum

The twelve principles of green chemistry were initially designed as a way to guide chemistry in a responsible manner. [13] There have been a number of references to the use of the principles as a way to enhance the curriculum and to provide a centre focus for a greener chemical education.

1. **Prevention**
   It is better to prevent waste than to treat or clean up waste after it has been created.
2. **Atom Economy**
   Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Syntheses**
   Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**
   Chemical products should be designed to effect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries**
   The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. **Design for Energy Efficiency**
   Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks**
   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**
   Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary

modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

9. **Catalysis**
   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation**
    Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-time analysis for Pollution Prevention**
    Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention**
    Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Figure 1.1 The Twelve Principles of Green Chemistry. [13]

Braun *et al*. have expressed how the use of these principles coupled with specific strategies can enhance and complement the current chemistry curriculum and assist in developing a curriculum that provides the first step in promoting the idea that green chemistry is essential to chemistry. The principles also serve as a reminder to those studying chemistry that it has both social and environmental impacts. [12] In addition to this, the adoption of the principles can benefit the curriculum further by providing a safer and more efficient working environment in the laboratory. [28] The principles also present a discussion point for students, where they can discuss concepts such as atom economy, chemical hazards, efficiency and laboratory safety. [8]

Stark *et al*. believe that the principles of green chemistry can allow students to judge the chemical transformations that they carry out in theory and practice and also understand the use of chemical compounds. [29] The University of Scranton, USA has adopted this approach in the form of the development of educational modules that can be used to infuse the principles into existing modules from organic chemistry to industrial chemistry. [30]

1.5.2.2 The use of green chemistry textbooks

Using green chemistry textbooks to bridge the gaps that a traditional chemistry degree may miss has been suggested as a way to incorporate green chemistry easily into modules by referring to green chemistry issues associated with the traditionally taught material. [6]

1.5.2.3 Laboratory classes

Laboratory classes are vital to a successful Chemistry education. Students learn the theory and principles of the chemistry that they are studying through lectures and discussions, however it is not until they are able to practise and apply the theory that they have learned in the laboratory that they begin to think critically about it. Students are said to often view lectures as abstract whereas they view laboratory classes as a more concrete activity. [8] Laboratory classes have been named as excellent vehicles for teaching green chemistry [15] and they provide the opportunity for a number of approaches including:

1.5.2.3.1 Alternative experiments

The simplest way in which to incorporate green chemistry involves the substitution of suitable experiments with new, greener ones. This requires little effort, and with the development of more and more green experiments, this will continue to become easier to do. There are a wide range of resources that are readily available for this, including regular articles within the *Journal of Chemical Education* detailing new experiments, the Green Chemistry Network, [31] The University of Oregon's Greener Educational

Materials for Chemists database [32] and a wide range of books such as Roesky and Kennepohl's, '*Experiments in Green and Sustainable Chemistry*'. [33]

1.5.2.3.2 Raising awareness of the dangers of chemicals

Green chemistry is associated with and promotes the use of environmentally benign reagents and renewable sources within the laboratory. A way to raise the awareness of this and the potential dangers that chemicals can present to both the environment and human health, is to ask students to fill in COSHH (Control of Substances Hazardous to Health) forms using material safety data sheets (MSDS) and databases. So that students do not feel put off by the overwhelming amount of information contained on an MSDS it has been suggested that specific areas such as exposure limits and handling precautions are focused on. [8]

1.5.2.3.3 The use of metrics and Pre and Post Lab Questions

Green chemistry metrics offer a way of quantifying how green or environmentally friendly reactions and processes are by measuring and monitoring them in terms of waste generation, efficiency and resource usage. Klingshirn has suggested the use of pre and post lab questions in which the atom efficiency metric is used. [8] The use of these questions can provide an opportunity for students to compare and contrast more than one route to a particular compound based on these issues and determine the advantages and disadvantages of each. These questions can also require students to consult material safety data sheets for information such as the toxicology of the materials that are being used.

1.5.2.3.4 Waste monitoring

Asking students to measure or calculate the potential amount of waste generation for the reactions that they are carrying out can allow them to understand just how much they are generating. If the type of waste is also monitored, this can help students grasp the concept of how it may affect the environment if it were to be released *via* for example, the drains. Students can also be asked to consider the cost of disposal, creating the link between the waste itself and how it should be reduced to save money as well as to be kinder to the environment. [8]

1.5.2.3.5 Microscale Chemistry

Microscale Chemistry is a lab-based, environmentally safe, pollution-prevention approach accomplished by using minature glassware and significantly reduced amounts of chemicals. [34] It began in the early 1980's within three institutions in the US, Bowdoin College, Merrimack College and Brown University. It was first introduced into the organic chemistry laboratory at Bowdoin College, Maine. It was then further introduced into other aspects of the chemistry syllabus, including inorganic, analytical, general and environmental chemistry.

The National Microscale Chemistry Centre has carried out a number of experiments to determine how effective it is as a method. They have found it to possess many benefits for use in the teaching laboratory, for example;

- A reduction of laboratory hazards due to reduced chemical quantities, this lowers the operational costs in the laboratory allowing a wider variety of alternative reagents to be used.

- Allows the green chemistry concept of feedstock substitution to be applied which results in milder reaction conditions and reduced environmental exposure.
- Microscale chemistry can be combined with the atom economy metric system.
- Allows the use of altered reagents, new reaction pathways, and alternative solvents, which in turn yields less hazardous products and by-products.
- Allows reactions to be chosen that require less extreme reaction conditions, shorter reaction times, and ambient pressure instead of high pressure and reduced temperature requirements.
- Shorter reaction times mean that the time to carry out microscale experiments can be 50% shorter than traditional experiments.
- Can be used as a pollution prevention methodology. [34]

A study carried out by Abdullah *et al.* [35] showed that the microscale method was just as effective as traditional-scale practical work. They reported that the teacher and the students all viewed it positively, and that the students received significant gains in their understanding of chemistry concepts. Although this study was not concerned directly with green chemistry it was encouraging to find that the benefits of microscale experimentation, as discussed above, (safety, economy, environmental and speed of experimentation) are obtained without losing any educational benefits.

1.6 Case Examples of Best Practise and Existing Chemistry Curricula

1.6.1 labRATS at the University of California: Santa Barbara

The Laboratory Research and Technical Support (labRATS) program at the University of California: Santa Barbara is a unique scheme that connects laboratory managers, students, academic and operations staff with each other. The scheme is conscious about increasing energy and resource efficiency and minimising environmental footprint as far as possible through the adoption of sustainable practices within the laboratory research environment.

In 2004 the Laboratory Research and Technical Staff (labRATS) program first began as a result of a researcher named Allen Doyle who looked into Sustainable Research. This involved looking into how researchers study within laboratory environments. He then began to compile a bank of sustainable practices within his own laboratory. These best practice examples range from energy usage to chemical control and cover a wide range of laboratory operations. Since then, the labRATS program has developed a set of simple yet effective materials to use within laboratories to aid in making it a more sustainable environment, for example, stickers to ensure that people remember to turn off equipment, and fume cupboard information to show just how much more energy is being used when the sash is left open.

These best practice examples form the basis of the labRAT laboratory audits that are used as a tool to find out just how environmentally friendly the laboratories are and to identify areas that can be improved. These audits look at power usage, room conditions, recycling, chemical usage etc and are used to make the laboratory a more sustainable and comfortable environment. [36]

1.6.2 Existing Chemistry Curricula

A number of undergraduate chemistry programmes at UK universities were looked at *via* their online prospectus and course information to determine how far sustainability and green chemistry had become included in current chemistry curricula. These courses were also looked at to determine whether they were embedded throughout the entire curriculum or as standalone modules. Standalone modules were then looked at to determine whether they were applicable to a specialised subject or just a general module introducing green chemistry and sustainability. The UCAS website was used as a tool to find courses and also well known and local universities were chosen. Specific examples of the findings have been presented below.

1.6.2.1 General Green Chemistry Modules

The University of Hull offers a range of chemistry courses and within these, modules such as 'Industrial and Environmental Chemistry' are included. This module introduces first year students to topics relevant to the chemical industry and the impact of chemistry on the environment. The learning outcomes of the module include; allowing students to discuss issues that are common within the industry such as industrial processes, economics, safety and the environment. The module also encourages students to evaluate environmental problems so that the impact of chemistry on the environment can be considered; which allows students to understand the role of chemistry in protecting the environment. This module takes advantage of the use of case studies covering topics such as bulk inorganic chemical production, pharmaceutical and agrochemical industries and environmental monitoring amongst others.

The University of Liverpool chemistry department offers a module in the third year entitled ‘Chemistry for Sustainable Technologies’ which is designed to introduce the basic concepts of sustainability and sustainable development, this module is similar to that offered by the University of Hull and includes learning outcomes such as; understanding and explaining the concepts and terminology of sustainability and sustainable development and green chemistry, recognising the importance of thermodynamic principles in judgements about what is considered sustainable, recognise the strengths and weaknesses of green chemistry and appreciate the importance of catalysis and the use of renewable feedstocks in developing chemical technologies.

The University of Nottingham offers an ‘Introduction to Green Chemistry and Processing’ module. The module includes teaching green chemistry in its broadest sense to provide an introduction covering the fundamental concepts of green chemistry and chemical applications. The module is designed to put the information received *via* the rest of the course into a green chemistry context and makes extensive use of case studies and structured examples.

There is evidence of modules like these at a number of other institutions including, the University of Leicester.

1.6.2.2 Green chemistry and sustainability and specific topics

A leading university in the field of green chemistry- the University of York, offers optional modules within the second and third years of their undergraduate chemistry degree programmes. The modules entitled 'Clean Technology- Energy and the Environment' and 'Clean Technology- Industrial Strategy and Planning', delve deeper into environmental issues, giving students an insight into how energy is generated and chemicals are produced. The 'Energy and the Environment' module considers the effects of energy input into the environment before discussing the different processes for electricity generation. The 'Industrial Strategy and Planning' module considers the production methods of chemicals and how the methods change due to the need to reduce costs and search for cleaner processes (for example, energy inputs, process safety, amount and cost of waste *etc*. The module also explores changes to the chemical industry and seeks to predict where it is heading.

1.6.2.3 Degree courses

Some universities offer degrees purely in the area of green and sustainable chemistry. Bangor University offer an 'Environmental Chemistry' undergraduate course, which involves some of the relevant degree-level chemistry such as molecular bonding and enzyme function, analytical chemistry skills such as trace pollutant measurements, data analysis and green chemistry, and the chemistry of the environment. The chemistry of the environment part of the course focuses on studies of the natural systems in the atmosphere, hydrosphere *etc* and describes changes which occur to unpolluted systems when the natural balance is disturbed.

The University of Edinburgh also offers a sustainability focused degree in the form of 'Chemistry with Sustainable Chemistry', however there is no further information available on the webpage regarding course content.

1.6.2.4 Green chemistry embedded into the curriculum

From the universities looked at *via* their online information and prospectuses and an internet search, there was no obvious evidence that suggested that green chemistry had been incorporated throughout the entire chemistry curricula of universities within the UK. It was not possible to look through every single curriculum in the UK but after an extensive internet search there was still no evidence of any curricula that had taken this approach. Outside of the UK, St Olaf University in Minnesota, USA has made efforts to embed Green Chemistry throughout its entire chemistry curriculum since 2003. This has been done through seeking ways to lower the environmental impact of experiments by using water-based and non-toxic chemicals, more efficient processes that reduce waste generation and as a result of this have reduced the number of energy intensive fume cupboards. The twelve green principles are also explored, which has made St Olaf University a leader in green practices and preparing graduates that understand how chemistry can impact on the environment.

During the pilot of the greening of the laboratories, students compared the effectiveness of traditional chemistry using toxic solvents to greener water-based chemistry. Students were asked after the pilot whether they thought that they had benefited from carrying out experiments with Green Chemistry in mind, students strongly preferred Green Chemistry because of its positive environmental affects. The following show some of the responses reported by Spessard from the students at St Olaf College [8]:

Yes, it made me realise how experiments can be performed using alternate chemicals that are safe for the environment and for people.

Emphasising green chemistry at the undergrad level makes it more likely that the students will continue to apply it in their future work.

1.7 Potential barriers to the inclusion of sustainable development within education

The Higher Education Academy produced a report in 2006 summarising the progress being made in Sustainable development in higher education and the current practise and future developments. [37] Research was carried out in seventeen of the academy's subject centres to determine the extent to which their disciplines were engaged with education for sustainable development and to discover good practise in the curriculum. The research highlighted four barriers to the successful embedding of education for sustainable development into the curriculum of many of the subject disciplines studied:

1. An overcrowded curriculum
2. Perceived irrelevance by academic staff
3. Limited staff awareness and expertise
4. Limited institutional drive and commitment.

Lecturers within the disciplines identified solutions to overcome the problems:

Barrier to sustainable development within education	Potential Solution
1. Overcrowded curriculum	Create space through a rigorous review of existing curricula Audit existing curricula to determine what is already there in terms of the development of identified ESD skills and knowledge

2. Perceived irrelevance by academic staff	Develop credible teaching materials which are fully contextualised and relevant to each subject area. This ensures that ESD is integral to the curriculum and not a ‘bolt on’ element
3. Limited staff awareness and expertise	Invest significantly in staff development and capacity building through institutional staff development units and Academy Subject Centres
4. Limited institutional drive and commitment	Develop a credible business case for HE institutions, setting out sustainability benefits Review and amend institutional mission and policy statements

Table 1.2 Barriers to the incorporation of Education for Sustainable Development

Although this was a survey of a variety of subjects, Braun *et al*. have commented specifically on how these barriers have become apparent within chemistry when it has been suggested that Green Chemistry should be incorporated into the curriculum. They comment on views expressed such as, ‘this is not the way that the real world works’, ‘traditional material is more important than Green Chemistry concepts’, ‘there is not enough time to cover the traditional concepts and include new ones’. [12] This shows a great reluctance to change, however with the above framework hopefully the counter arguments towards green chemistry can be eliminated.

1.8 Summary

This literature review has provided an overview of the concept of sustainability, drivers for green chemistry, potential ways to integrate sustainability into the chemistry curriculum, potential barriers to inclusion and solutions and examples of best and current practice within the green and sustainable chemistry area. The information regarding courses at other institutions can hopefully be used to shape the chemistry curriculum at the University of Bradford in the best way and begin the move into teaching green and sustainable chemistry. It is possible to take inspiration from others for curriculum content, especially from leaders in the field such as the University of York, UK and St Olaf College, USA, in developing a greener curriculum. The drivers for green chemistry such as the recent introduction of REACH legislation show that this subject is growing and that there is a need for chemists to have an awareness of the issues surrounding green chemistry, as it is here to stay.

CHAPTER TWO: Student Perceptions of Green Chemistry and Sustainability

2.0 Introduction to using qualitative research within Chemistry

A literature search has shown that there is a gap in the research of student perceptions of green chemistry, some feedback to the introduction of green chemistry within the curriculum at St Olaf College, USA is reported in chapter one, however this did not address the issues that this study has intended. In the cases of a lack of published research, qualitative research is a useful way of exploring the perceptions that people may have of certain issues. [38] Qualitative research is something that is not usually associated with chemistry, and rare in this environment. As a result of this it was important to obtain some data on student perceptions of green chemistry, sustainability and environmental issues in order to inform curriculum development and to improve their student experience.

2.1 Aims of the Student Perceptions Study

Currently the Chemistry curriculum at the University of Bradford does not contain any material related to Green Chemistry and Sustainability. The aim of this project is to introduce concepts related to Green Chemistry and Sustainability and as an objective it was important to gain student perceptions of the following:

- Degree of awareness of the topic and how they view sustainability and green chemistry.
- What our students already know.
- What they would like to be taught.
- How they think sustainability and green chemistry should be taught.

- How they currently work in the laboratory and whether they have any ideas for improvement.

2.2 Data Collection Plan

To collect the student perception data, a multi-method approach was used consisting of questionnaires, discussion groups and observation of these groups. These multiple data collection sources provide a triangulation of evidence; Denzin defined triangulation as, 'the combination of methodologies in the study of the same phenomenon'. [39] Campbell and Fiske used triangulation and developed the idea of multiple operationalism. They argued that in order to validate evidence it was important to use more than one method so that any variance between response was due to that of the trait and not of the method itself. [40] This therefore develops the confidence that the results are valid and not a methodological artefact, giving the research validity. A critique of the data collection approaches will be offered within the related method sections.

2.2.1 Groups

Two groups were chosen to collect data from, first year undergraduate students and MSc postgraduate students. These groups were chosen to find out whether or not there would be any difference in perception and knowledge between students that have already completed a science degree and those who are just starting one.

1. MSc Analytical Sciences students

   A session was held for the MSc students (n=16), with optional attendance. This included a brief introduction to Green Chemistry and the twelve green principles [13], and the UNESCO definition of sustainability. [41] The students were split into two groups and prompted with questions to give their opinions and thoughts on green chemistry using the UNESCO definition as a talking point. Questionnaires to find out about current laboratory practise, thoughts on green chemistry and how much the students already knew were handed out before the beginning of the session. These questionnaires also acted as a pilot for the first year students. Evaluation questionnaires of the session were distributed after the session.

2. Undergraduate first year Chemistry students

   Data was collected from the first year students in two sections. The questionnaires that were handed out to the MSc students were given to the first year students (n=53) to fill in after a scheduled lecture. There was also a separate discussion session that was held, with optional attendance to talk about green chemistry, sustainability and current practise with the students (n=10).

2.3 Methods of data collection

The following sections detail the data collection methods used in this study.

2.3.1 Observation

Observation is described as the systematic viewing of people's actions and the recording, analysis and interpretation of their behaviour. [42] Observation provides researchers with the opportunity to document behaviours, activities and events of people without relying on self-reports by individuals which may not always give accurate representations of those activities or events. [43]

Observation has three main elements:

- Watching what people do
- Listening to what they say
- Sometimes asking them clarifying questions

There are a number of advantages and disadvantages of using observation as a method of data collection. Observation can be extremely useful method, as already mentioned it provides researchers with data that could otherwise be lost by inaccurate representations given by the group studied or by people not giving as much information. A disadvantage of this method is that some forms of observation can elicit what is known as the *Hawthorne Effect.* This is where people taking part in a study modify their views, opinions or actions in order to please the observer, this may lead to inaccurate results. [44] If the observer is placed among the group being observed they may also influence events and people. This can be avoided with the use of covert observation. This, however can be regarded as a contentious issue especially in relation to ethical issues arising from the observation of students. This will be mentioned in more detail later in this chapter.

The analysis and interpretation of observation work can also pose a challenge. The interpretation of what is observed may be influenced by the mental constructs of the researcher [42], this includes their own personal values, prejudices, motivations and emotions. Important evidence and data may be disregarded as researchers often only 'see' what they want to 'see.' A second opinion of the interpretations may help to avoid this occurring. When the data is analysed, extracting themes and concepts can be quite challenging, this is another area where data rich in evidence may be lost, again a second opinion may help to overcome this problem. An independent check of the data was carried out by the supervisor of this work, in order to ensure that no evidence was lost due to it being over-looked.

2.3.1.1 The use of observation in this study

Saunders *et al.* differentiate between methods within observation as *participant* and *structured* (also known as non-participant observation). [45] Participant observation is being involved and collecting data that is mainly descriptive- *qualitative*. This approach to observation is known as qualitative as the results and data collected from this method are interpreted in the context of the environments and situations in which they occur [43], it also emphasizes the **meanings** that people give to their actions. In participant observation, the researcher becomes a member of the group being researched and so experiences the same situations as them, this helps the researcher to understand their situations. [42] Structured observation includes gathering data in a specified way and counting and classifying what is seen- *quantitative*. This form of observation focuses on the **frequency** of the peoples actions. [42] The observer does not interact with the group being studied and aims to be as discrete as possible. This method of observation means that the behaviours of the people are not influenced and thus there is less opportunity for research findings to be biased in any way. [46] This type of observation was not applicable to this study in this context as it was more about exploring the student perceptions and views.

Participant observation was used in this study as it was felt that only questionnaires as a method of data collection could result in the loss of important qualitative comments from the students. Observation would also pick up the actions and feelings of the students and it was possible to see the areas that they felt strongly about through the way that they behaved and the areas that they put emphasis on.

A challenge of participant observation is maintaining the correct ‘insider’/‘outsider’ balance, it is important that the researcher is both physically and emotionally close to the people within the study in order to get the most out of the session in terms of data collection and evidence, whilst still sustaining a professional distance. To remain as an ‘outsider’ to the group could mean that the method used would not be as successful as a rapport is not formed between the researcher and the participants of the study. Merrian *et al.* state that the boundaries for the ‘insider’/‘outsider’ status are not clearly defined or simple. [47] As described by Hall, the best way to maintain this status is to negotiate a position in which one is in some way, ‘at home’ and considered as ‘one of us’ without becoming completely immersed. [48] The groups that took part in this study were already familiar with the observer and as a result a rapport already existed between the participants in the study and the observer, it was also made clear to the group how essential it was for them to be honest, building trust between the groups and the observer.

The methodology of this approach is not designed to produce results that are able to be generalisable to a wider population, but to explore and attempt to explain behaviours in the context of the studied people’s lives, traditions and situations. However, some data and findings may have the capacity to be transferable to other populations or communities. Therefore these findings may provide useful starting points or hypotheses for researchers in other settings. [46]

Participant observation can be further classified into *overt* and *covert* observation. Overt, as the name suggests is where those being observed are fully aware that the observation is taking place. In contrast to this, covert observation is where the participants are unaware that they are being observed. One of the main arguments for the use of covert observation is that it removes the risk that people may change their behaviours and actions, as they are unaware that they are being observed, therefore the validity of results is not threatened. One of the problems of using this method, however, is that it can be seen as being unethical. People may not feel happy about the thought of being watched and used in a study without their permission. [42]

Although covert observation could perhaps provide more accurate results, this would not have been acceptable in this research situation and it was more beneficial to make the participants aware of what they were taking part in, as already mentioned, to build further rapport and trust between the observer, the participants and the facilitators. Although the issues discussed within the discussion groups were not particularly sensitive in terms of personal issues, ethically it was better to be more open with the group as it gave them the chance to leave if they did not feel that they wanted to take part.

2.3.1.2 Documenting field notes

An extremely important part of participant observation is to keep a written record. [43] According to Bailey, field notes are 'the backbone of collecting and analysing field data'. [49] To allow accurate record keeping and structure throughout the observation process, the following checklist proposed by Spradley [50] was used to construct the context of the observation. (See Appendix A for example of field notes).

1. Space: the physical space or spaces
2. Actor: the people involved
3. Activity: a set of related acts people do
4. Object: the physical things that are present
5. Act: single actions that people do
6. Event: a set of related activities people carry out
7. Time: the sequencing that takes place over time
8. Goal: the things people are trying to accomplish
9. Feelings: the emotions felt and expressed

2.3.2 Questionnaires

2.3.2.1 The use of questionnaires in this study

In addition to the observation of discussion groups, questionnaires were used. According to Gillham, questionnaires are of most value when used in conjunction with another method of data collection. He comments further, 'This multi-method approach to real-life questions is important, because one approach is rarely adequate; and if the results of different methods converge then we can have greater confidence in the findings.' [51] This is in agreement with the 'triangulation' of evidence, mentioned earlier.

Questionnaires are just one of a range of ways of getting information from people, and perhaps one of the most popular tools for gathering data. [42] Of course, as with the use of any data collection method, there are advantages and disadvantages to the use of questionnaires. In favour of questionnaires is the fact that they are relatively low cost in time and money which is often a major factor in research, a thousand questionnaires could be sent out in the time that it would take to do two semi-structured interviews. [51] It would take far too long to interview all the participants taking part in this study, and as a result this is why questionnaires were chosen. It was also felt that it would be the best way to gather information from such a busy group of people, quickly and in reasonably large volumes.

Depending on the organisation of handing out questionnaires, it is usually relatively easy to get information from a lot of people in a reasonable length of time; in contrast, interviews could take large amounts of time with very little information gained, depending on what is being asked. Respondents may also prefer this method of data collection as they can remain anonymous and feel freer to give truthful answers, however others may be cautious about committing their answers to paper. A downside to this is that the researcher cannot tell who has responded and who has not and so prompting those who have not may be difficult without contacting the entire group. [52]

Low response rates are recognised as quite a large problem with this method, however, a 'captive group' [51] such as students in a lecture hall, can overcome this as the participants in the study are asked to fill in the questionnaire before leaving the activity, without additional demands on their time. This methodology was employed after the first group session with the MSc Analytical Sciences students (n=16). (See reflections on data collection methods). Dillman suggests that a number of factors are involved in achieving a high response rate; these however are mostly related to postal questionnaires. He suggests ideas such as, developing an easy to complete questionnaire with clear instructions of how to complete it, this was used as part of the questionnaire design. [53]

Filling out a questionnaire can also remove the risk of interviewer bias, research into this area has shown that different interviewers will receive different answers. [51] Factors such as perceived race, gender, social class, age and education can all contribute to the answers that people give. Interviewer bias can also be the result of the skills of the researcher, showing just how critical they are to the success of the interview. [42] Bias may also be removed by the standardisation of questions, this only applies if the participants all understand the questions in the same way. The way that questions are worded can sometimes have a negative effect on the quality of answers, research has shown that only slight differences in the way that questions are phrased can cause extreme polarisations in response due to not interpreting the question in the way it was supposed to, for this reason the questionnaires involved in this study were piloted to remove any uncertainty in questions. [51]

The amount of time needed to complete the questionnaire will also determine how many responses are obtained and as a result of this questionnaires should be kept short. [51] The questionnaires were limited to twenty quick answer questions using the Likert scale, a form of a scaled response question and some open questions. Motivation is also a key part of receiving questionnaires, unless the respondent sees some personal relevance or something interesting and worthwhile to complete they are not always bothered about filling them in. For this reason, the purpose of the project was explained, so that the students participating could see the potential value of the activity. [51]

Research has shown that if questionnaires are not well developed and presented in a logical order then this can have an effect on the quality of the data collected. This also applies when respondents choose questions at random and do not answer them in the order intended. This is because the respondent does not allow the responses to develop in the sequence intended [51]. To avoid this, the participants in the study were given clear instructions of how to fill in their questionnaires, both on the questionnaire itself and through the introduction at the beginning of the session.

2.3.3 Questionnaire development

The questionnaires used within this study were developed using inspiration from other sources such as the Fisher Scientific educational materials [54] available online. These general questions, based around the environment, were used as a starting point for the questionnaires. There were four sections to the questionnaire including:

- General awareness of environmental issues and green chemistry
- Responsibilities as scientists
- Current laboratory practise
- Awareness of chemical legislation

The questionnaires contained a mix of both open questions and those using a Lickert scale [42] (scaled response questions), both of these forms of question were used in order to give the participants more freedom in answering and to add structure. They also provided variety in order to make the questionnaire a little more interesting to fill in. This was also an attempt to create a high response rate in terms of students answering every question.

2.4 Reflections on data collection

2.4.1 Observation

2.4.1.1 MSc Analytical Sciences Group

On reflection, the observation of this group was difficult after the introduction of the session as they split into two separate groups, this was in order to give small enough numbers of people so that there could be more discussion made between participants. As a result of this, they were placed on different tables, separate from each other. It was hard to record all events and quotes of the two groups as my complete attention could not be given to both at the same time. Instead of trying to record both, when I heard something that students felt strongly about, I would attempt to listen in to that group and concentrate on this, for example, when the student mentioned, 'they just threw copper sulphate down the sink, it kills fish!' this caught my attention as the student gave so much emphasis to this and it was obvious that they felt strongly about this particular subject. This was the first time that I had taken part in observation, and I found it an interesting tool to use. It was also very tiring and quite intense towards the end of the two hour session. Roper *et al.* comment that long periods of observation can be tiring which can lead to vigilance decreasing over time. In a study carried out they reported that there were no significant differences between the first ten minutes and last thirty minutes of recording, however this time period was not long enough to show any clear effects. A subjective assessment showed that observers tend to tire after two hours, [55] which suited the observational studies carried out with the students as the sessions were designed to last no longer than two hours. As a way to completely remove the risk of observer fatigue Latvala *et al.* suggest the use of videotaping [56], which also allows the full richness of the emotions, comments and actions of the groups being observer to be captured. The small scale nature of this research meant that this was not feasible as other data collection was taking place, meaning that realistically this could not be carried out in order to complete everything within the time-frame allocated for the project.

Although both groups could not be given my full attention, the group sizes were helpful as they were small enough to capture what the participants were saying, without a large number of people talking at the same time.

After the session, some of the students expressed an interest in more sessions just like this. A lot of them showed that they were extremely keen to learn more about green chemistry and sustainability.

2.4.1.2 First Year Chemistry Students Group

Participant observation worked well with this group. To begin with I was able to observe the entire group as a whole, but as one of the facilitators had to leave part way through the session, I had to observe and facilitate. However, as the students were aware of my role and a rapport had been built, when I heard quotes that were interesting and relevant to the aim of the session they allowed me to write it down without much interruption to the discussion. My field notes were also written up immediately after the session so that ideas and suggestions, perhaps not written down in the session could still be recorded.

As a result of not having enough facilitators, I could not observe the second group, however flipcharts were used to record the students' thoughts and ideas which mostly mirrored those of my group, so the data lost was minimal. The suggestion made by Latvala *et al*. [56] to use videotaping recording as a method of participant observation would have been useful in this instance and if the study were to be repeated in the future, it would be considered as part of the data collection plan.

The group were extremely positive about the aspects of green chemistry, sustainability and environmental issues that we discussed. They showed great enthusiasm and interest in this subject and made it clear that they would definitely like to learn more. Even after the session students approached me to ask about having more sessions like it and were also keen to set up a green chemistry group within the department.

2.4.2 Questionnaires

2.4.2.1 Pilot questionnaire and modifications

The questionnaire used for the student participants within this study was piloted in the first session with the MSc students. (See Appendix B for copy of questionnaire). These students were used to pilot the questionnaire as the group was much smaller than that of the first year students, so it was thought that if certain aspects of the questionnaire were not understood, that a large amount of data would not be lost. The first year students were also the main target for the data collection as the ultimate aim of this project aims to embed sustainability and green chemistry into the undergraduate curriculum.

When analysing the results of the pilot questionnaire it became apparent that some questions had not perhaps been understood and interpreted in the way that they were supposed to and as a result some responses were not very useful. The following questions were modified to direct the student to think about the specific areas within the question.

4. Do you think green chemistry has an impact on everyday life?

A comment given to this question, ‘most people are a long way removed from the chemical industry,’ suggested that perhaps some students do not realise the connection between products in the home, and that they are in fact developed by the chemical industries. This question was meant to prompt the students to think beyond the green chemistry area. The responses given show that this question did not achieve this and that it should be rephrased so that the purpose of the question was clarified. To give more direction for the students, the question was changed to the following:

> **Do you think that green chemistry has an impact on everyday life?**
>
> For example; in the manufacture of products for the home

18. Do you consider why you are using a certain reagent/solvent?

This question was designed to prompt the student to think whether they realise the function of the chemicals that they are using, for example if it is needed to act as a nucleophile etc. When asked after the session, some students expressed that they were not entirely sure what they were being asked. As a result of this, the question was changed to the following in order to direct the student to the area that they should be thinking in and to remove any difficulties in answering the question:

> **Do you know the function of the reagent that you’re using and the part that it plays in your reaction?**

For example; the reagent acts as a source of Cl^- for the reaction to proceed, or the reagent acts as an electrophile

19. Do you consider how much washing solvent you are using?

In the pilot study carried out, seven out of thirteen students agreed or strongly agreed that they do consider how much washing solvent they are using. This was extremely surprising as it was expected that most would disagree with this question due to the comments made in the observation session with the MSc students. If students were asked for a rough number of how much washing solvent they use, it would be expected that they may not be able to give this number, the question was therefore added to, in an attempt to get the students really thinking about how much they use and as a result of this, how aware they are of what they are currently practising in the laboratory. The question was modified to the following:

Do you consider how much washing solvent you use?

For example; If you were asked how much acetone you had used to clean a flask could you give an accurate answer?

After modifying the questions and giving the students a little more direction, more comments were made in the areas that were expected and it was clear from the responses that there was less confusion.

2.4.2.2 Response rates

The questionnaire data relating to student perception was collected easily as a 'captive' audience was used as according to Gillham. [51] As a result of this, response rates were high for both the MSc students and the first year chemistry students. Evaluation questionnaires were also developed according to a template used within the School of Pharmacy at the University of Bradford and given to the MSc group after the discussion session. The response rate for these questionnaires was extremely low (twelve percent response, n=2) as the students were allowed to take these away as they felt that they needed to think about things further and were tired from the session. It did not seem appropriate at the time to ask the students to stay, especially as they had expressed how they did not feel that they could complete them to a good standard. The students were asked to hand their completed questionnaires in to the general office within a week, giving them sufficient time to complete them and to remove the chance that they may forget about it (and the details of what they really thought of the session). After this time period and several follow up emails providing a copy of the questionnaire, there was still a low response. Moore comments that reminders are most effective when they are sent with a second copy of the questionnaire in the case that it was lost. [57] This low response rate showed just how effective the use of a captive audience is in generating a high response to questionnaires. If this was to be repeated it would be advisable for students to fill questionnaires in before they left the session, using a 'captive' audience once again.

In the literature there are many references to low response rates being a major issue with the use of questionnaires. A large number of these references are present within the field of Healthcare. Templeton *et al*. carried out a study of general practitioners to determine whether or not a low response rate matters. They concluded that low response rates can introduce the risk of non-response bias, however it need not affect the validity of the data collected. [58] Robson comments that non-response is a serious issue for postal questionnaires, and just as serious for other forms of survey but perhaps easier to avoid. [59] In the context of this study, it was not imperative that the evaluation questionnaires were returned as the main aim of the study, to gather the student perception of green chemistry and sustainability, was completed and was not affected by this. However, if this was to be repeated to find out how effective the discussion groups were, as discussed earlier, a captive audience would be used. Lensing *et al*. also comment on how being creative with how participants return questionnaires can increase response rate. They were able to increase the rate in a survey of physicians by giving the option of receiving and returning a questionnaire by fax, thus making it easier for them. [60] Perhaps in a university environment, the use of electronic tools and e-questionnaires could increase the response rate amongst students that did not wish to fill in a questionnaire within a captive audience.

As the session held for the first year chemistry group did not include much teaching and was mainly a way to obtain data on their views of green chemistry and sustainability, the use of evaluation questionnaires did not seem appropriate to use.

2.4.2.3 The Amount of Data (Observation and Questionnaire methods)

Each observation session (The two groups: MSc students and first year chemistry students) lasted approximately two hours. The number of students participating from the MSc Analytical Sciences and First Year Chemistry group were an accurate representation of the usual group sizes of the students enrolled on these courses.

Although the sample of observations is relatively small in comparison to other studies, the data was rich in evidence and provided insight into how the students perceive green chemistry. Other studies may contain hours and hours of observation; however this was not the intention of this work. The observation, in parallel with the questionnaires were intended to provide a starting point for the development of a green chemistry and sustainability component of the practical side of the undergraduate chemistry courses. This was also only one aspect of the design, as research was also carried out in other areas, for example Green Chemistry Metrics. (See Chapter Four).

2.5 Results and Analysis

2.5.1 Observation Field Notes

2.5.1.1 MSc Analytical Sciences Students

The observation session with the MSc Analytical Sciences Students consisted of a stimulated discussion session by facilitators and the use of handouts with information relating to green chemistry, the twelve green principles [13] and the UNESCO definition for Education for Sustainable Development. [41] Twelve students (n=12) were involved in the discussion session as four (n=4) of the students had to leave after filling in their questionnaires due to other commitments. The students involved in this session came from mixed backgrounds, some of which had previously completed their undergraduate degrees within the sciences at the University of Bradford, and some had completed their undergraduate degrees at other institutions around the United Kingdom and overseas. For the full field notes refer to Appendix A.

After the observation took place, the field notes were written up and sections were expanded with data that was not written down due to lack of time. The data written up after the session were items such as some of the suggestions made by the students for improvements to the laboratory areas. The notes were then coded according to themes that seemed to emerge. Boyatzis describes thematic analysis as a process for encoding qualitative information. [61] It is used as qualitative approaches are thought of as being extremely diverse and complex, Braun *et al*. recommend that it should be seen as a foundational method for qualitative analysis. [62] The encoding requires an explicit code which can be in the form of a list of themes. Boyatzis describes a theme as being a pattern found in the data that at a minimum can organise and describe possible observations, or at a maximum can help to interpret certain aspects of the phenomenon. [61]

Codes were given to the data in order to arrange it into categories to make the data more manageable. Without breaking it down, the data can appear confusing. To begin with the field note data was highlighted each time a different theme seemed to emerge. Once this had been carried out, these codes and themes were further coded as some topics fitted together and were more easily understood than being analysed on their own. For example, responsibility and changing the thought process of people, and toxicity and laboratory practise.

Initially it was difficult to know how far to break the data down, but coding once and then coding a second time to make links made this process easier.

2.5.1.2 Findings

Several themes emerged from the observation field notes. These were mainly based around laboratory practise and education, the main themes were:

- Laboratory practise; current and future
- Education and the future
- Responsibility
- Raising Awareness
- Drivers for sustainability

Findings are presented with specific examples from the field notes collected at the time of observation. Individual quotes are presented alone, whereas dialogue is given in one section with quotation marks, square brackets indicate where a quote is given but not necessary exactly as the student said it. The findings are presented using the following to show groups and individuals:

FA = facilitator

F = female participant

M = male participant

G = group

Numbers correspond to the individuals and groups.

Laboratory practise; current and future

Laboratory practise was a major talking point throughout the observation. Both current and future laboratory practise were discussed. Students expressed how they do not always know why they are doing what they are doing in the lab.

> No one tells me why I'm doing it this way; we just do it the way we're told. G2F3
>
> 'Don't just do something, know why you're doing it, we need a more in depth understanding of things, not just random, have insight in what you're doing.' G2F3 The conversation moves into how things are done at the university and practical lab classes, two females from group one, 'we're just told to do that, not why we're doing that.' 'We just do it, we have no understanding of what we're doing.' G1F4 'There is a need for insight and direction.' G2F1
>
> People follow scripts and don't question them. People use acetone for washing, too much, what a waste. G1M1

These quotes show concern from the students, and show that laboratory sessions will require students to be given a greater understanding of why they use a certain chemical, why they use a certain method and why they are learning that particular chemical technique. This would work well with introducing green chemistry and sustainability. If students are not aware of what they are doing and the hazards associated with a certain chemical, they would not be able to suggest substitutes or other methods that would be more environmentally friendly. This does not mean to say that students should be given all the answers and the reasons for using a certain technique or chemical, they can also be asked to find these things out for themselves, as developing critical thinking skills is part of the aim of the programme.

Toxicity was also a theme within laboratory practise that students showed quite a lot of concern over. The group were asked what they think about the UNESCO definition for sustainable education. The group began to think about working in the laboratory and without much prompting, how labs create toxicity in the outside environment.

> We shouldn't just look in the lab and at the people in the lab, we should look outside the lab, we should be worried! G2F2

The concern showed here was very high. The student has again linked the lab work that they carry out, to the outside world. The two individuals involved in this conversation mention how filtration can reduce toxicity by taking out the toxic components of reaction media. These comments showed that the students are aware of ways to reduce toxicity themselves. They also mention how they would choose solvents with the lowest toxicity, this is something that students should definitely be thinking about as legislation comes in and some solvents and chemicals are restricted (see Chapter One for information regarding legislation).

> They just threw copper sulphate down the sink, it kills fish! G1F2

When this student said this quote, they said it with great emphasis, making it clear that they felt very strongly about this subject. This shows that there is a need for a transfer of information. This student knew that this was wrong, however the person throwing the chemical down the sink could have not been aware of the damage that this could cause, not been aware of the correct disposal routes, or was not really bothered. If students can start to use peer assessment and act on what they see and help each other to realise that what they are doing could be changed to benefit the environment, this could be a way to change for the better.

Raising Awareness

Raising awareness is a theme that was apparent throughout the observation, that students felt is needed. When talking about how some people behave in the lab this was one area that was suggested.

> People in general don't take much care, they don't recycle properly. G1F2
>
> I think it's more about awareness. G1M2
>
> We need more information, you could do something like showing a picture of a dead fish killed by throwing chemicals down the sink. G1F1

Showing students a picture of a dead fish might be potentially traumatic for students and too drastic for raising awareness, but it shows the magnitude of what the students think needs to be done in terms of raising awareness and showing the importance of good laboratory practise.

Students spoke about laboratory practise and methods and procedures used.

> 'Who will create methods in the future?' FA1

> ‘Students.’ G2
>
> ‘Can you do anything now?’ FA1
>
> ‘We need awareness, tell people it is wrong and why it is wrong. It’s all about knowledge and opportunities’ G2F1

This quote again comes back to the point addressed earlier about informing students of why they’re doing a certain thing. Raising awareness is a key starting point, without it students cannot change.

The facilitator in group two presented the students with an idea about introducing a way to measure the impact of their laboratory work.

> ‘How about we use an *envirometer*? If it went off the scale would you change your practise? If you can see it does it make you more aware? Should we assess the impact?’ FA2
>
> ‘It would be good if you could type your chemical in and get a better one.’ G1M2

The students didn’t really respond to this idea, but instead suggested their own such as the one above about substituting chemicals for more environmentally friendly ones.

Some of the students within the group that had studied at the University of Bradford as undergraduate students attended a Royal Society of Chemistry Green Chemistry lecture in their final year, which gave an introduction to what green chemistry is, why it is needed, alternatives *etc*. This had inspired some of the students within the group to change their current practise due to being more aware that what they were doing could have a negative impact on the environment.

> I took no care, didn’t think about what I was using, how much I used or the disposal of it. It is careless and never crossed my mind. The green chemistry lecture made me think. G1M1

> After that lecture I went back to work, where we use 100-200 aluminium trays a day for testing. I thought that it costs more to extract aluminium than recycle it so I asked my boss if we could change and get recycling bins. G1F1

The fact that this lecture had such an impact on the thought process of these students is extremely encouraging. Perhaps without that lecture, students would have carried on doing the same things in the lab as they have always done, not because they want to have a negative impact on the environment, but because they have never been told any other way. Students need to be taught about environmental issues and alternatives in order to change their current practise to a more environmentally friendly one, perhaps this could be delivered in pre lab sessions.

Students that had previously worked in industry had also experienced a similar situation where their awareness changed the way that they work in the lab.

> [Methanol was used a lot in experiments with no care or safety, but then after a safety workshop we found that it was toxic to women so we tried to reduce its use in the lab, a different, lower toxicity solvent was used.] G2F2
>
> [How about more PPE?] FA1
>
> [We just substituted it for diethyl ether.] G2F2

This shows that being given the extra bit of information through lectures and workshops has changed the mindset of these students. It cannot be said for sure that giving lectures would affect all student's attitudes towards the way they work, but it could make them think more about what they are doing and consider the idea of using alternative solvents, reagents or methods, managing waste more effectively and the hazards of chemicals at a personal and an environmental level.

Who's responsibility is it? Changing the thought process

Understanding who the responsibility lies with in terms of practising in an environmentally friendly way is an important part of changing the thought process of laboratory users. If they do not understand where their personal responsibility lies then it is often thought that someone else will do it and as a result good practise is not followed.

> 'Who's responsibility is it [to make sure things follow best practise]?' FA2
>
> 'Everyone's responsibility I think. Not just companies, people in general as well.' G1F2
>
> 'The problem comes when people don't want to change. [Can't put something down the sink, don't want to change, too much hassle and they think that it's not their problem.]' G1F3

Students need to understand that changing to another way of working does not always mean that it will be more hard work. The group also talked about driving factors and how reputation and behaviour will determine who takes responsibility.

> People don't want to look lazy. G1F2
>
> Some people are lazy and don't want to change, for example, 'I want to go home it's 5 o' clock, shove it down the sink. G1F1

Having confidence to change was also an important point raised. Some people are worried that they will find another method more difficult, and as they are out of their comfort zone of their usual practise, they may feel uneasy trying out another method. This is demonstrated by the quote below when asked to changing to recycling solvents and waste rather than putting it down the sink.

> [The problem doesn't stop there though, how about disposing of waste bottles? Should we instead consider recycling?] FA2

> ‘At work we use acetonitrile, there’s a shortage of it at the moment, we use it but then we get it back out- recycle it. Some people don’t have the confidence to do it.’ G1F2

If students are given training of how to perform tasks such as recycling solvents, they may feel that in a laboratory within the university or in industry, that they would have the confidence to try it for themselves, this could help to avoid situations like the one mentioned above.

Education and the future

Education is one of the most fundamental ways to get the message across to students, this was a key aspect of the qualitative comments given by the students that took part in this research. The group saw education as a main way to change and that it can help change the future.

> [Education is someone standing up and acting on green chemistry.] G1F2 The group continue to talk about education changing the future. A girl in the group started talking about the future and what will happen to the environment if nothing changes. [In 2050, the ice caps will be molten.] G1F3

The students related education to real world situations which was a positive output from the study. Instead of introducing this topic as a standalone subject it was envisaged that it would be embedded into the current curriculum. Subjects such as global warming and pollution are commonly seen in the mass media such as the news and newspapers and it is encouraging to see that the students already see some link between their education and courses at university, and what is happening in the real world.

How the students think green chemistry and sustainability should be taught came up in the conversations amongst the groups. Having an insight into how the students would like to be taught and why can help to deliver the appropriate material in the most effective way.

> The group begin to talk about how to get the message across. 'Make things more interesting' G1F1
>
> 'I don't think green chemistry should be taught lecture style, it needs to be more interesting and hands on.' G1F2

After the success in changing the way that the students practise in the laboratory due to workshops and lectures, it would seem that lectures should not be completely removed as a tool to teach this area. Combining pre-lab sessions to give knowledge and understanding of what the students are doing and why, with the practical aspect of the course means that they can learn the theory and see it in practise, as chemists, the practical aspect should satisfy the need for hands on activities. It was suggested that instead of a one way transfer of information, a two way learning process is used in lectures, workshops and lab classes, the following were suggested as ways to promote a two way transfer of ideas and information.

> Feedback in design, freedom to change, pre lab assessments, giving students time to think about what they've done/ are doing, COSHH assessments in parallel with a system that is more environmentally friendly. FA2

Students also believe that sustainability and green chemistry should be introduced as early as possible.

> 'We thought it would be best introducing at early levels.' G1F3
>
> An example is given to the class about recycling and if it is introduced early on that it becomes routine and doesn't feel like extra effort. FA1
>
> 'The challenge is motivating people to do things.' G1M2

This piece of the observation shows that people are able to work in a sustainable way; it again is about the thought processes of the people involved. If something, such as recycling, became second nature it would not seem such a hassle for students to do it.

Allowing students to design their own experiments would also make them think about what they are doing rather than just doing something because they have been told. There is a lot of evidence in this observation to show that students are not thinking for themselves as much as they would like to, if they just follow scripts and do not challenge the way that they are doing things, change cannot occur.

> 'At York we had to design our own experiments and think about what we were doing.' G1F2

This gives further evidence that the design stage is important to enable students to think.

2.5.1.3 First Year Chemistry Students

Ten first year chemistry students (n=10) attended a discussion session. Most of the discussion within this session was based around education. This was stimulated mostly by the facilitators to get a feel of what students think will work best and what they want to know. The group was split into two separate groups of five students in order to allow small group discussions to take place and as a result only one group was fully observed, and short notes were written down by the second group. (See reflections on data collection methods).

2.5.1.4 Findings

Several themes emerged from the data after coding using thematic analysis. The majority of the observation quotes were reported from the observation of one group of five students. However, many of the themes present mirrored those of the second group. Single quotes are presented alone without quotation marks, square brackets indicate a quote which may not have been the exact words that the student used, dialogue is presented as one section with quotation marks.

The findings are presented in the same way as those of the MSc group, using the following:

FA = facilitator

F = female participant

M = male participant

G = group

Numbers correspond to the individuals and groups.

Laboratory practise: current and future

This theme is one that was also apparent in the observation of the MSc students.

The students within the discussion group identified waste as a major issue within the laboratory and managing it properly as a way to improve laboratory practise in terms of sustainability. This has been the first issue that students think must be resolved.

> [How about sustainability in labs?] FA1
>
> 'It could be improved by not pouring everything down the sink- when I started my lab work I thought there would be somewhere to put the waste, like a specific box or bottle, but it went down the sink and into the environment.' G1F1

Students seem to be aware that what they are doing is not quite right but without being told how to handle the waste, they just see pouring it down the sink as a quick and easy solution to get rid of it, and in some sense, the only way to get rid of it. If students are prompted to think about the hazards of the chemicals that they are using, they could perhaps begin to challenge the way that waste is disposed of, instead of just doing what they are told to do and act upon this.

Waste in terms of water and power usage was also recognised by the students. The following example was suggested in relation to the amount of water that is needed to cool a condenser during reflux or distillation.

> 'Imagine how much water you'd save if you had it on a water pump, the only problem would probably be cooling the water, but if there was ice at one end or something, that might work.' G1M2

Here the student has recognised how much water is unnecessarily wasted each time a reaction using this method is carried out, and attempts to suggest a way around this.

This could suggest that they are not oblivious to the impact on the environment that their reactions might have. Suggesting ways to improve their work in terms of sustainability is positive, as they are not just looking for the answers.

In terms of the apparatus used in the lab, students identified water baths as being wasteful as they 'leak too much' and are always on when they're not needed. Sharing apparatus and working in groups was suggested by the group as a way to reduce waste and energy usage.

> [The only problem with group work is some people do all the work and some do none] G1M2
>
> [But there are benefits, because we'd cut down on waste and solutions.] G1F1
>
> [We could maybe heat solvents in one conical flask and share it instead of heating loads of small flasks of solvent.] G1M3

The above dialogue of the students showed how one tried to challenge the idea of working together and couldn't see a benefit to it and only the negative side, student G1M2 tried to challenge this by showing the student the benefit to the environment by cutting down on waste and resources. Student G1M3 translated this into an example and made a suggestion of what could be done in the lab. The students also applied this to synthesising products as a large batch and splitting it down so that individuals could continue the rest of the experiment.

The students considered the entire laboratory process without any prompting; including the washing up after the experimental section is over. Students were keen to put their ideas and suggestions forward of how to improve the labs in this particular aspect of the practical work that they carry out.

> [In our last lab session we used two big bottles of acetone just for washing up.] G1M3

[The acetone should be the last thing to use if the water doesn't clean it, we should be encouraged to use the washing up liquid and the brushes and only use acetone if it won't come off.] G1F1

'How about something like some 'how to wash up' posters by the sinks? Would that help?' FA2

'Yes and then students know how to do it properly.' G1F1

[We should also be told how to wash up properly without lots of solvent before we come into the lab, like before the very first session.] G1M1

[We need to wash in washing up bowls too, instead of under running water, it's a waste.] G1F1

The students here have recognised that acetone should not be used in the volumes that it currently is being used in. Sometimes students can fail to realise that acetone is not just for washing but is a chemical in itself. The fact that they have noticed the amount that has been used is also encouraging, this points to them having some awareness of what they are doing in the laboratory and the impact they are having. The students have also shown that they are aware that there may be alternatives to the way that they currently wash up in the lab and only using solvents as a last resort of cleaning. Waste was mentioned again, one student thought it would be better to use washing up bowls rather than running water as it is a waste of water. From this data it cannot be said for certain that students thought this during their lab classes, or that the discussions of sustainability triggered some of these ideas, however, the ideas are again encouraging and show that the students are realising that they can practise chemistry in a more sustainable manner.

The idea of having an introductory pre-lab session for new students, including a 'how to wash up' section, would hopefully make this a routine part of the lab experience, meaning that students would not have to change the way they do things later on in their university careers. Introducing this straight away would allow students to use best practise right from the beginning of their degrees.

As already mentioned, reaction size and scale came up as a point in the conversations. However, this raised a point not dissimilar from the work carried out with the MSc Analytical Sciences students who mentioned that some people do not have the confidence to change.

> [How about changing the sizes of your experiments?] FA2
>
> The group thought that this could work but would be better in the later years of their university careers.
>
> [Because not all of us are that experienced when we first come to university I don't think that we should scale down in the first year because you might need one gram of something but not get it, but as we become more experienced, it will work. It's like we had to do an experiment and needed a gram for the next bit but some people didn't get it.] G1M1

The concern expressed about reaction size could have been showing a lack of confidence in the student's own ability. The reaction sizes that are used in the undergraduate labs are of a much larger scale than those that would be typically seen in a research lab within the university or industry. Therefore it would probably be beneficial to them to practise on a smaller scale from the beginning of their degree courses to gain experience. It would also be beneficial in terms of sustainability as reagent costs would decrease due to less being needed, less waste would be generated and therefore waste disposal management would be easier.

> [It's like we had to do an experiment and needed a gram for the next bit but some people didn't get it.] G1M1

This part of the observation shows how students are worried by not having enough of the product of the synthesis. If one gram is needed and is not obtained, the student could scale down the reagents used in the next part of the synthesis to enable the reaction to be performed. This can be mapped to the MSc students, and how they want to be more aware of what they are doing rather than just following a script. Giving the students more confidence to do this would hopefully mean that reactions could be scaled down to benefit all areas of sustainability- socially, economically and environmentally.

Education: Learning the theories with application to the real world and the practical components of the course

During the discussion group, changing education and introducing sustainability was a concept that was explored by the students. Students expressed what they would like to learn more about, including more efficient fuels and alternative energies, decontamination of industrial waste and how to begin to solve some of the environmental problems such as pollution.

> [What would be attractive to you to learn about?] FA1
>
> ‘More efficient fuels and alternative energies.’ G1F2
>
> ‘We don’t know how long it is until fossil fuels run out but they are running out.’ G2F1

The fact that student G2F1 has expressed that they do not know how long it is until the fossil fuels run out could signify that they want to know more about this issue, they already realise that this resource is low and want to learn the alternatives to be ahead in the knowledge for the future. This also shows that students have been given some sort of introduction to this subject, perhaps at school, or just through the information in the media, such as adverts on the television and reports in the news. The students were keen to know about current problems within chemistry and the chemical industry, but not just that they exist; they made it very clear that they would like to have enough knowledge to attempt to work out a solution to these problems.

> [We don't know about any problems, only those that we see in the media.] G2M4

As already mentioned in the example relating to fossil fuels, students emphasised again that they do not know about issues relating chemistry to the outside world. This is obviously something that they are keen to know about as there was great emphasis from the students about not only knowing the theory of green chemistry but also being able to apply it to real life situations and to practise it in the laboratory.

> [We also want to apply green chemistry to specific cases, not just learn the theory.] G1M3

Students expressed their interest and enjoyment in the learning activities that they were introduced to as a part in their organic chemistry modules.

> Dr X does some Eco-chemistry in his lectures, it's interesting because he asks us to look into disasters and see what has happened. G1M1

Whilst the students spoke about this they seemed enthused and made it clear that it was a highlight of their lectures and something that they would like to do more of. Along with solving problems, students suggested learning more about what other people and research groups have done within the field of green chemistry so that they remain up to date with the latest discoveries and technologies. They also communicated their interest in knowing current environmental issues, and if they were to be told more about them, they thought that this would keep them engaged and interest them more.

In terms of delivering material on sustainability and green chemistry, there was a mixed response, some of the group suggested an optional module, compulsory modules and interactive sessions as a part of lectures, workshops and taking part in group work. At this stage there was no mention of the practical side of the course, but students suggested substituting some of the material in their professional skills module for a green chemistry and sustainability team building activity. The students here are not disregarding green chemistry and treating it as a side arm of chemistry, it is something that they are willing to try out and embrace into what they are studying.

> [In the labs there could also be a green chemistry practical like cleaning contaminated water or something, so then we'd have organic, inorganic, physical and green chemistry.] G1F1

Student G1F1, as well as a few others from the group, is very focused on knowing how to manage the after effects of not practising green chemistry, rather than attempting to redesign chemical synthesis and reactions to prevent having to 'clean up' afterwards. It is interesting that the students have not really considered this concept, which is something that could be introduced to them through lectures and the practical aspect of the course.

The group were asked what they thought about integrating green chemistry and sustainability through theory or through practise.

> 'So do you think that the best approach is to have a small compartmentalised activity module as the theory or a matter of routine in practise?' FA1
>
> 'Both need to be implemented to understand the theory but also need to know how to apply it too.' G1M2

> [We could have it in our labs and learn the theory in the pre-labs, then apply it in the lab sessions.] G2F3

It was positive to see that, without any prompting, the group were keen to receive theory in pre-lab classes and practise it in their labs so that they can apply it. The group stressed throughout the entire discussion that they need to know how to apply it, not just know about it.

In terms of the practical module that is part of the first year, one of the students suggested using metrics to measure the impact of their experiments. Metrics had been briefly mentioned at the start of the session as an introduction to the project and students had picked up on this.

> [Instead of repeating questions, like in the physical chemistry experiments, we could have a series of calculations based on green chemistry.] G1M3
>
> [We would need to learn about metrics in the pre-labs and it would probably be best the week before so that we have time to understand it and go over it in our own time.] G1F1

It seems from this part of the data that students do not enjoy the repetition of questions in the physical chemistry experiments and would prefer to replace them with something that they see as being interesting and perhaps beneficial to them. Suggesting being taught about metrics in their pre-labs and having the time to study them properly so that they gain a good understanding of them, shows that the students are serious about taking on this aspect of chemistry and fully integrating it into their normal laboratory practise. This shows that they are not treating it as a side arm of chemistry, but seeing its importance and benefits.

Raising Awareness

Awareness was an issue raised within most of the discussions, the students made it obvious that they do not know enough. The group was asked where they would like to be in terms of their awareness.

> 'In terms of your Chemistry4 careers, where do you want to be in terms of awareness?' FA1
>
> 'Implementation of green chemistry to make a better impact on the environment.' G2F2
>
> 'Do you see this as a research opportunity?' FA1
>
> [Yes it would be nice to be aware of where things are now and how the environment is now so that in the future it can be pushed forward and improvements can happen.] G2F1

Student G2F1 has shown that they see that they may, in the future, see them self as being responsible for dealing with or suggesting ways to impact the environment in a positive way. They see their education as the vehicle delivering this information, to direct them in the right direction and allow them to improve things in the future.

As part of their laboratory routine, the students believe that they should be aware of the hazards of chemicals that they are using.

> [We need to be aware of the hazards of chemicals, what they do to us and to the environment, we don't ever really know and it is only once or twice that we have looked at them, and we didn't know how they affected the environment.] G1M1
>
> [How to you think it would be best to do this? Would it be best for you to be given a COSHH form? Or for you to fill out a COSHH form yourselves?] FA2
>
> [We should fill in the COSHH form ourselves and for most experiments, this would be good because we know the hazards and we also have experience of using the forms.] G1F1

At present, students are rarely asked to fill out a COSHH form; therefore they are not exposed to the information and remain unaware of all of the hazards of the chemicals that they are using. Some laboratory scripts will contain warnings if a particularly hazardous material is being used, but there is usually no mention about the toxicity of the chemicals to the environment. It is encouraging to find that the students are interested in knowing the hazards of the chemicals that they are using and have shown concern over not knowing them. The COSHH form would ensure that students are definitely researching the chemicals and would allow them to have easy access to the information whilst they are working in the lab.

We don't know!

On more than one occasion throughout the discussions, students stressed how they do not know enough. Some of them expressed how interested and keen they are in learning more about environmental issues and how to solve them.

> [What sorts of things do you think we can do to improve?] FA1
>
> 'Run more workshops about the subject, we don't know enough.' G2M1
>
> 'What do we need to get people in to begin with?' FA3
>
> 'People don't understand so we need to have an understanding of why it's important which should then make people want to come to sessions.' G2M1

It was interesting how student G2M1 thought the reason why some people remain ignorant to green chemistry and sustainability and do not make any effort to understand it, is because they do not understand it in the first place. The student also thought that once others knew why it was so important that they would be encouraged to attend more sessions. It is as though people attempt to remain oblivious to these issues until they have to, and once they realise that they are not just something that is of the moment, but how it will affect the future some become more inclined to learn more. The issue here is again awareness, which the students were explicit in mentioning throughout the session.

As already mentioned, the students had various examples of where they do not know things that they would like to know. Such as the hazards of the chemicals that they are using, what is going on in terms of environmental issues of the moment, legislation, and not understanding this topic in general.

The students could find out the hazards of the chemicals that they are using themselves, but seem to need direction at this stage, they want to be told to do this and have it as an integral part of their lab sessions. Without being prompted to find out about these issues through their course, it seems that some of the students perhaps do not know where to start to find this information, what to look for, what to learn about. They may be feeling that they need a push in the right direction and need to be given the support and confidence through their course to do this.

Employability

Many of the students involved in the discussion believed that the concepts of sustainability and green chemistry were very important in terms of their future careers as professional chemists. Some also believed that knowing about legislation, although they were not aware of it to begin with, would also be important in terms their employability.

> 'How much in terms of legislation?' FA1

‘We don’t know.’ Most of the group.

‘A lot of legislation is coming in, especially in chemistry which requires some change and better documentation of chemicals. Do you feel that knowing this is important in terms of your employability?’ FA1

‘Yes because the environment will get more and more important as time goes on, if we know about legislation then it’ll be good for us.] G1F2

Within the session, some students showed that they wanted to be able to apply any theory learnt in lectures or workshops to industry. It was obvious that they thought that this would be an important factor in terms of going into the chemical industry as a professional.

The importance of sustainability for the future

At the beginning of the discussion with the first year students, they were prompted to give their views on what sustainability means.

‘What do you understand by sustainability?’ FA1

‘to make things last longer.’ G2M2

‘conservation.’ G1F3

‘not using excessive amounts.’ G2M1

‘Do you make any decisions based on sustainability within your course?’ FA1

‘Not in my course, but in my life, such as recycling.’ G2M2

‘In the labs I don’t weigh out excessive amounts and I try not to spill things so they’re not wasted.’ G1F2

These students showed that they have an understanding of what sustainability means, and that they are already trying to implement some of the positive aspects of sustainable practise into their everyday lives. As already mentioned, the students feel that they do not know enough in terms of their education, but if some of them are already familiar with sustainability, it is easier to build their knowledge without having to convince them that it is something that will impact them in a positive way, mainly in terms of their future as professional chemists.

In contrast to this, one student showed their negativity towards sustainability, identifying it as a ‘hot topic’ and ‘fashionable.’

> [How important will this topic be in a few years?] G1M2
>
> ‘It’ll always be important, the environment is becoming more and more important.’ G1M3
>
> ‘But it wasn’t twenty years ago, it’s like a hot topic at the moment and it’s fashionable to be green. It’s like we recycle but then it has to be transported to China so really defeats the point of recycling in the first place because fossil fuels are used to transport it.’ G1M2

G1M3 was quite defensive at this point, expressing how important this issue is. G1M2 could be seeing this topic as a waste of time and makes it quite clear that they think that it will come and go, like ‘fashion.’ The fact that the student mentions that sustainability was not important twenty years ago could signify a lack of understanding of how things have developed in the environment in terms of pollution or using up resources, or perhaps how we have only just recognised how important this subject is.

On the other hand, G1M2 could also be showing a high understanding of these issues. They talk about how people make the effort of recycling, but then the waste is put on a ship, so in effect they are seeing a positive impact on the environment such as recycling, being balanced out by the negative impact of putting it on a ship, to take it across the globe, using fossil fuels; therefore using up valuable resources and releasing greenhouse gases into the atmosphere in the process. It is not surprising that some students may view sustainability in this way, as they do not always see a positive impact, and could just view this as a waste of time in terms of learning and practising in a sustainable way- both within their personal lives and their university careers. Because of this, the positive sides of practising sustainability and green chemistry must be stressed to a maximum to allow these students to understand the benefits.

2.5.2 Analysis of Questionnaires

2.5.2.1 MSc Analytical Sciences Students

Questionnaires were handed out at the beginning of a Green Chemistry discussion session with the MSc Analytical Sciences Students (refer to appendix B for copy of questionnaire), which also involved observation throughout (see section 2.5.1.1 for findings). Sixteen students attended the session (n=16), some of which had previously completed their undergraduate degrees within the sciences at the University of Bradford, and some who had completed their undergraduate degrees at other institutions around the United Kingdom and overseas. There was a one hundred percent response rate (n=16) for these questionnaires.

To analyse the data, the qualitative comments were coded and themed. Several themes emerged when coding the data collected from the questionnaires filled in by the MSc students. They were mostly based around the environment, the main categories were:

- Environment
- Environmental Chemistry
- Safety
- Pollution
- Money
- Education
- Chemicals

In order to validate these themes and to ensure that there were not any that were overlooked, an independent check of the data was carried out by a supervisor.

2.5.2.2 Findings

The following shows the responses given on the questionnaires by the MSc students. In some cases students did not answer all questions.

	Yes		No		Total
Question	N	%	N	%	
Q1. Are you aware of Green Chemistry?	8	57	6	43	16

Table 2.1 Summary of results from questionnaire to MSc Students

Q1. Are you aware of Green Chemistry?

There was quite a large polarisation in response to this question. 43% (n=6) of the group were not aware of green chemistry, however these results were not particularly surprising as there was no expectation.

Q2. What do you think of when you hear the words 'Green Chemistry'?

When asked what the students thought of when they hear the words green chemistry, there were several themes that emerged from the data. Seventy seven percent (n=13) of responses included the words 'environmental' or 'environment.' These included those such as:

> Mainly about chemistry of the environment, what it is composed of, what it contains, interactions and so on.
>
> Trying to make chemistry more environmentally friendly.
>
> I think it's a subject about chemical compounds and their effect on the environment.
>
> This is a new thing or method to protect the environment

Comments about pollution and safety were also common:

> Relation between chemicals and safety and the environment.
>
> Using of safer chemicals in relation to the environment.
>
> The relation between chemical material and the environment, for example, chemical gases produced by cars and the effect that this gas has on the environment, the green chemistry will reduce the pollution.
>
> The chemistry with regards to reducing waste, pollution etc. Better synthetic methods, recyclable elements.

This showed that the majority of the class, although not all were aware or familiar with green chemistry, associated green chemistry with the well being of the planet.

	SA		A		NSF		D		SD		Total
Question	N	%	N	%	N	%	N	%	N	%	
Q3. Do you think Green Chemistry can make a difference to the planet?	5	42	6	50	1	8	0	0	0	0	12
Q4. Do you think Green Chemistry has an impact on everyday life?	2	15	8	62	1	8	1	8	1	8	13
Q5. Do you think that Green Chemistry is important?	2	14	11	79	1	7	0	0	0	0	14
Q6. Do you feel future employers will require you to have knowledge of Green Chemistry?	6	55	4	36	1	55	0	0	0	0	11
Q7. Do you think Green Chemistry can work?	3	25	6	50	2	17	1	8	0	0	12
Q8. Would you like to learn more about Green Chemistry?	4	29	8	57	1	7	0	0	1	7	14

Table 2.2 Summary of results from questionnaire to MSc Students

Q3. Do you think Green Chemistry can make a difference to the planet?

The response from the students was extremely positive with ninety two percent (n=12) of people agreeing that green chemistry could make a difference to the planet. There were no negative responses. The environmental theme was present again, with comments including:

> It plays an important role to protect the environment.

> I think less chemicals used, less pollution in the environment.

> Making a cleaner, non toxic planet.

Q4. Do you think that Green Chemistry has an impact on everyday life?

There was polarisation in answers when asked this question. The majority agreed that it does, but there were also comments including:

> Most people are a long way removed from the chemical industry.
>
> Too early, the subject is still peripheral.

These comments showed that the question had not been interpreted in the way that it was intended. This was discussed in more detail in the reflection section (Section 2.4).

Q5. Do you think Green Chemistry is important?

The majority of the sample (n=13) agreed that green chemistry is important, one answer was no strong feeling, but no one disagreed with the question. This is a positive output as a large number of the students had never heard of it before. Comments included:

> Yes to protect the environment from any more damage.
>
> Especially important in extracting rare elements from phones etc.

The latter comment was interesting as it mirrored an issue that had been covered in a Green Chemistry lecture delivered by the Royal Society of Chemistry at the University of Bradford.

The environmental theme was again present throughout the comments and there were two references to the safety provided by using Green Chemistry and references to life:

> To work in a safe environment.

> It will help to give safe life without any problems.

> Yes, from both sides, in work and in everyday life.

These students have not just related Green Chemistry to their University careers but also to life in general, which is positive when considering that some did not see the link in the previous question.

Q6. Do you think future employers will require you to have knowledge of Green Chemistry?

Ninety one percent (n=10) of students responded with either strongly agree (n=6) or agree (n=4) in response to the above question. There were no negative responses to this question, and one response to no strong feeling. This question showed a lack of comments, however those recorded were associated with importance and improvement of green chemistry and things in general:

> To help improve the green chemistry.

> Yes, it will be more important in the future than it is now.

> They would like us to have an idea of the affects that we have on society and nature, and ways to help improve things.

The last comment also mentions some of the building blocks of sustainability- society and nature (the environment).

Q7. Do you think green chemistry can work?

This question was answered very positively with only one student disagreeing. The comment given with the strongly disagree response was:

> Advancing sciences, advancing experiments, more experiments and more bi-products.

This response was in a complete contrast with another comment made by a student:

> Developing new methods using less chemicals.

The negative comment was interpreted as the student thinks that the incorporation of green chemistry will cause more problems than helping to solve them. The majority of the sample (n=9) strongly agreed (n=3) or agreed (n=6) that green chemistry can work. Two students showed no strong feeling.

There were three references that suggested that effort will be required to make it work:

> Yes if people are prepared to make the effort.

> With time and effort.

> Yes but it isn’t easy to achieve.

Q8. Would you like to learn more about Green Chemistry?

When asked if the students would like to learn more about green chemistry there was a small polarisation in their response, however most remained positive with seventy five percent (n=12) students strongly agreeing (n=4) and agreeing (n=8) that they would like to learn more.

There were two references made to the importance of the subject:

> It has an important role in the future.

> I would because I think it is very important, however I also think it’s boring. It needs to be made more interesting for teaching.

This latter comment shows that if green chemistry is going to be incorporated and make a difference to the way that the students learn, it must be taught in a variety of ways in order to keep students interested.

There were references to wanting to know more and one student showed interest through the following comment made about a project with an optional topic:

> I am researching it for my project.
>
> We should learn about it more.
>
> I would definitely want to know a bit about the concepts of it.

One student related green chemistry to the work that they carry out in perhaps in both their university work and a job:

> That considers a part of my work as an analyst.

This comment was encouraging as this student has not regarded green chemistry as a separate branch of chemistry but something that would go with the work that they carry out.

	Yes		No		Total
Question	N	%	N	%	
Q9. Are you aware of the 12 green principles?	3	21	11	79	14

Table 2.3 Summary of results from questionnaire to MSc Students

Q9. Are you aware of the twelve green principles?

The twelve green principles of green chemistry act as a guideline of how to practise chemistry in the most environmentally friendly way. [13] When asked if the students had come across the principles, only twenty one percent (n=3) were aware of them. It was expected that there would not be many people that knew about the principles, as they are specific to green chemistry.

Q10. What do you think the advantages of using Green Chemistry are?

Seventy five percent (n=12) of students responded to this question. Themes consistent with those already seen such as the environment were present.

> Help against environmental problems.
>
> Environment, money.

There was the introduction of new themes such as waste reduction and changing practise for the better:

> Less waste, more recycling, reduced synthetic steps, use of catalysis therefore obtaining better reaction stoichiometry.
>
> It would be efficient, cause rethinking and redesigning of old practise.
>
> Reduction of harmful processes.
>
> Reducing waste.

Two responses related green chemistry to the chemical industry itself:

> It is very important in the industrial environment area.
>
> More important in industry.

Q11. What do you think the disadvantages of using green chemistry are?

Sixty eight percent (n=11) of students responded to this question. In comparison to the advantages, many of the students related the disadvantages of green chemistry to cost. With fifty five percent (n=6) giving this response.

> Probably more costly.
>
> None, maybe cost but not sure.
>
> Difficult and expensive.

Effort and time to achieve green chemistry practise was also present as a theme again, with comments including:

> Effort, change.
>
> It may be expensive, it will take time to obtain this.

One student's comment was quite confusing, it could be that they misinterpreted the question, or they genuinely do not think that the use of green chemistry will give any benefit and will instead make things worse.

> Causes environmental pollution.

Q12. Do you think that the planet has environmental problems?

Seventy five percent (n=12) of students responded to this question, all of which reporting that they believe that the planet does have environmental problems.

A theme of pollution was present within the comments made:

> Yes in terms of pollution.

> Yes, like air pollution, gases.

> Yes too many, too much pollution and the wide range of pollution.

There were also two references to issues that are commented on in the media:

> Especially the ozone layer.

> Cities drowning.

This could be an indication that the media is the main source of this type of information for the students, as currently their education is not responsible for their knowledge of these topics.

Q13. How do you think environmental problems may be solved?

Eighty seven percent (n=14) of students responded to this question. It was left as an open question so that the participants had the freedom to give whatever answer they believed would solve environmental problems.

There were three main themes that emerged from the data. Education was a key response, with four students commenting in this area:

> By educating people and making them aware of correct disposal routes.

> Education.

> Education and money, lots of money.

People and society were also present as a theme:

> Political groups throughout the world need to reduce all factors that contribute to poor green chemistry.

Fundamental societal change, global-local.

Less people.

By work, get all the people together to protect the environment.

Chemistry itself and the practise involved were also thought of as a solution:

By using chemical compounds in the right way.

To get progress in chemical material that doesn't affect our environment so badly.

There were two references made to pollution:

By decreasing the pollution from different sources that causes it.

By discarding unwanted pollutants and know how to do this.

All of these responses show that students believe that environmental problems are not just going to go away on their own and there is a requirement for societies, education and research to work together in order to reduce them.

	SA		A		NSF		D		SD		Total
Question	N	%	N	%	N	%	N	%	N	%	
Q14. As a scientist do you feel that you have a responsibility to be green?	5	36	9	64	0	0	0	0	0	0	14

Table 2.4 Summary of results from questionnaire to MSc Students

Q14. As a scientist do you feel that you have a responsibility to be green?

Eighty seven percent (n=14) of students responded to this question. The response was extremely positive, with all participants either strongly agreeing (n=5) or agreeing (n=9) that they have this responsibility.

Although there were not many comments left in relation to this question, the three that were given all showed how strongly the students believed their responsibility, and not always through their university careers or jobs, but also in life itself:

> Everyone has this responsibility.
>
> I think all people have a responsibility to protect nature.
>
> If I may be contributing to chemistry, especially with the production of toxic compounds and the using of much energy, all approaches should be taken to reduce this.

Q15. How can we be more responsible in the lab?

Sixty eight (n=11) of participants responded to this question. Again this question was left open for students to give their views. Waste and disposal routes were an obvious theme amongst the responses, over half (n=6) of the responses were concerned with this theme:

> By using correct disposal routes.
>
> Only using the amount of chemicals needed instead of wasting so much.
>
> Less waste, ensuring correct disposal.
>
> By disposing of the chemical material in the suitable place for this material.

Students also commented on following correct procedure and safety and having awareness of what they are doing and why:

> To follow the safety rules.
>
> Follow safety instructions.

By knowing the rules/procedures in it and by being aware of what we're doing. If you don't know something, don't do it.

One student commented:

Dilution is the solution to pollution.

This comment is quite interesting, as it seems that the student may believe that this is a simple answer to one aspect of behaving responsibly in the laboratory.

	Yes		No		Total
Question	N	%	N	%	
Q16. Do you routinely design your own experiments?	4	29	10	71	14

Table 2.5 Summary of results from questionnaire to MSc Students

Q16. Do you routinely design your own experiments?

Eighty seven percent (n=14) of the group responded to this question. Seventy one percent (n=10) reported that they do not design their own experiments, this was not a surprising outcome as students had not yet begun their practical projects as part of their course.

Question	SA		A		NSF		D		SD		Total
	N	%	N	%	N	%	N	%	N	%	
Q17. Do you look for using alternative, more sustainable reagents?	2	17	7	58	1	8	1	8	1	8	12
Q18. Do you consider why you are using a particular reagent or solvent?	4	31	6	46	3	23	0	0	0	0	13
Q19. Do you consider how much washing solvent you use?	2	15	5	38	4	31	1	8	1	8	13
Q20. Do you use correct chemical disposal routes?	4	31	6	46	2	15	1	8	0	0	13
Q21. Would you be prepared to change your current lab practise in order to incorporate green chemistry?	8	62	4	30	1	8	0	0	0	0	13

Table 2.6 Summary of results from questionnaire to MSc Students

Q17. Do you look for using alternative, more sustainable reagents?

Seventy five percent (n=12) responded to this question. There was some polarisation in response, however the majority either strongly agreed (n=2) or agreed (n=7) that they do look for more sustainable reagents in their work. This result was quite surprising as it was expected that if most of the students do not design their own experiments that they would not feel the need to look for these reagents. However, it could be the case that they are interested and feel strongly enough about the issue of sustainability and green chemistry that they feel they should look up these reagents. As bias cannot be completely removed, these answers may also have been caused by the fact that the respondents felt that it would be a good thing to do and would please the people reading the questionnaire answers.

Q18. Do you consider why you are using a particular reagent or solvent?

Eighty one percent (n=13) students responded to this question. The majority strongly agreed (n=4) or agreed (n=6) that they do consider why they are using a particular reagent or solvent. The remaining respondents (n=3) reported no strong feeling.

Two comments given were related to laboratory practise:

> I consider if it is appropriate for what I intend to do.

> Normally most of the synthetic methods help to produce less waste and complete everything in the smallest amount of steps.

One student showed no strong feeling to the statement due to having:

> No Chemistry background.

Q19. Do you consider how much washing solvent you use?

Eighty one percent (n=13) students responded to this question. There was a range of response, however the majority (n=7) either strongly agreed (n=2) or agreed (n=5). These results were slightly surprising as students had already commented that waste and resource usage was a problem.

Two students were in disagreement with this, and one comment showed how they believed that it is secondary to their work:

> Experiment quality is more important.

This student is perhaps viewing green chemistry and best practise as a separate thing to what they are trying to achieve in terms of their experimentation in the laboratory environment. This is one barrier that will need to be overcome in order to introduce sustainability into the curriculum effectively.

Q20. Do you use correct disposal routes?

Eighty one percent (n=13) students responded to this question. There was again a range of response, however the majority either strongly agreed (n=4) or agreed (n=6) that they do use correct disposal routes. These results were again quite surprising as students had commented on waste and disposal routes as being a way to become more responsible in the laboratory so it was expected that this practise was perhaps not yet in place.

Correct protocols and legislation were present as comments:

> Always follow protocols.
>
> Driven by legislation and COSHH.

The following comments were given about ease of disposal:

> I try but not always.
>
> Normally if the correct disposal container is to hand.

This could signify that unless disposing of chemicals safely is made easy to do and without much more effort, the correct procedures will be followed, however if not, the chemical could end up going down the sink.

One student reinforced the point of waste being a problem:

> Waste in the wrong areas is one of our biggest problems.

Q21. Would you be prepared to change your current lab practise in order to incorporate green chemistry?

Eighty one percent (n=13) students responded to this question. There was an extremely positive response to this question, with ninety two percent (n=12) of the group strongly agreeing (n=8) or agreeing (n=4) that they would be prepared to change their current practise. There was no negativity towards this question in terms of response. There was a lack of comments however one student commented that:

> We need it also to give improvement in chemistry and performance.

It was encouraging to see that although it was a small group, the vast majority would be prepared to take this new laboratory practise on as part of their course.

	Yes		No		Total
Question	N	%	N	%	
Q22. Are you aware of current legislation regarding the use of chemicals?	5	36	9	64	14

Table 2.7 Summary of results from questionnaire to MSc Students

Q22. Are you aware of current legislation regarding the use of chemicals?

Eighty seven percent (n=14) of students responded to this question, with a large number (n=9) of them reporting that they are not aware of current chemical legislation. It was expected that the number knowing about this area could be quite low as the information is usually concerned more with industry.

2.5.2.3 First Year Chemistry Students

Questionnaires were handed out to first year chemistry students (n=53) at the end of a lecture (Refer to Appendix B for copy of questionnaire). This was done in order to get the highest response rate possible. The majority of these students had recently completed their studies at college or sixth form in the United Kingdom, with a small number from overseas and were now taking subjects within the area of chemistry at the University of Bradford. There was a one hundred percent (n=53) response rate for this questionnaire.

To analyse the data, the qualitative comments were coded and themed. Several themes emerged when coding the data collected from the questionnaires filled in by the first year students. They were mostly based around the environment, the main categories were:

- The environment and eco-issues
- Education and Chemistry
- Money
- Recycling and waste
- Pollution
- Global warming

In order to validate these themes and to ensure that there were not any that were overlooked, an independent check was carried out by a supervisor.

2.5.2.4 Findings

The following shows the responses given on the questionnaires by the first year students. As with the MSc students, some did not answer all questions.

	Yes		No		Total
Question	N	%	N	%	
Q1. Are you aware of Green Chemistry?	18	34	35	66	53

Table 2.8 Summary of results from questionnaire to First Year Chemistry students

Q1. Are you aware of green chemistry?

All students (n=53) responded to this question, with two thirds of the group (n=35) reporting that they were not aware of green chemistry.

Q2. What do you think of when you hear the words green chemistry?

The theme of the environment was obvious when analysing the responses to this question. Out of the fifty three responses, thirty six concerned it with this theme. Comments included:

> Environmentally friendly chemistry.
>
> The environment and recycling.
>
> Chemistry that doesn't harm the environment.
>
> Environmentally aware of what chemicals do to the world.
>
> Chemistry that's good for the environment.
>
> Chemistry that is not, or at least as little as possible, harmful for the environment.

Although a large number of students had not heard of or encountered green chemistry before, it was encouraging to see that they still showed some understanding of what the term might mean. Amongst these comments was the theme of being eco-friendly:

> Eco chemistry or science which helps or investigates eco solutions.
>
> Producing eco-friendly chemicals.
>
> Chemical reactions that are eco-friendly.

There were several references made to issues common in the media:

> Cleaner, more efficient, less toxic, less burning, less CO_2.
>
> Ozone friendly.
>
> Organic chemistry that is changed to be more environmentally friendly, not CFC's which cause and impact on global warming.
>
> The study of how reaction by-products could be made to be better for the environment, eg. Less CO_2 emissions.

Some students (n=5) commented on green chemistry being associated with renewable sources of energy and resources and alternatives:

> Development of alternative sources of energy.
>
> Sustaining the natural environment and finding alternative methods to save energy and improve efficiency.
>
> Renewable sources and environmentally friendly chemistry.

Recycling was also present as a theme:

> Recycling.

Nature, recycling, purification, trees.

Recycling, development of alternative energy resources.

Trees and recycling.

	SA		A		NSF		D		SD		Total
Question	N	%	N	%	N	%	N	%	N	%	
Q3. Do you think that Green Chemistry can make a difference to the planet?	18	34	23	43	11	21	0	0	1	2	53
Q4. Do you think that Green Chemistry has an impact on everyday life?	12	23	28	52	13	25	0	0	0	0	53
Q5. Do you think that Green Chemistry is important?	20	38	25	47	8	15	0	0	0	0	53
Q6. Do you feel that future employers will require you to have knowledge of Green Chemistry?	13	24	19	36	18	34	3	6	0	0	53
Q7. Do you think that Green Chemistry can work?	10	20	25	50	14	28	1	2	0	0	50
Q8. Would you like to learn more about Green Chemistry?	15	30	24	48	9	18	1	2	1	2	50

Table 2.9 Summary of results from questionnaire to First Year Chemistry students

Q3. Do you think Green Chemistry can make a difference to the planet?

Although the entire group did not report that they knew what green chemistry is, seventy seven percent either strongly agreed (n=18) or agreed (n=23) that green chemistry can make a difference to the planet. These results were overwhelmingly positive, as this could perhaps reinforce why the students must take this area of chemistry on board with the rest of their courses within the chemical sciences.

There were several comments relating to this question based around the theme of being eco-friendly:

> If green chemistry is eco-friendly, perhaps it will help reduce climate change.
>
> Can be more eco-friendly, less pollution = cleaner environment and less substances affecting the ozone layer.
>
> Pretty much everything we rely on has roots in chemistry/chemical production so creating eco-friendly and sustainable processes is vital.

Pollution was also mentioned throughout the comments:

> Using natural resources which cause less pollution.
>
> Recycling stuff could save a lot of space in landfills, less pollution.
>
> Most pollution is from chemical industries.
>
> Some are more immediate than others. Like stop pumping chemicals into a river that can kill fish.

Alternative resources and practise were present as themes among some of the comments already mentioned as well as the following:

> Reusable material reduces the input of dangerous gases, also reduces cost.

There were a few references to how green chemistry may not make a difference:

> Depends on what because whatever you produce, it will always cause some damage even if it is minimum.

> Some may be too long term to work.

> Only if a great amount of people use it.

There were also a number of comments reinforcing the fact that some of the students do not know about green chemistry.

Q4. Do you think green chemistry has an impact on everyday life?

Students responded to this question with a high percentage of them either strongly agreeing (n=12) or agreeing (n=28) that green chemistry has an impact on everyday life. It was encouraging to see that they had made the link between everyday products and processes and that green chemistry could be a part of this. The group mainly seemed to focus on the products after production, rather than during.

Recycling and waste management were made reference to on more than one occasion, with comments including:

> Recycling saves energy.

> In the creation of recyclable materials.

> Recyclable materials.

> It has helped to reduce household waste.

The products produced by the chemical industry were mentioned:

> Less harmful substances to the atmosphere by using green chemistry to establish new products.

> Everyone is concerned about less packaging and CO_2 emissions yet there is more to worry about than this.

> Chemistry has an impact on everyday products. If these are formed using green chemistry, this would be a great help.

Q5. Do you think green chemistry is important?

Again, there was a positive response to this question, with no responses indicating that the students disagreed that green chemistry is important. The majority of the group reported that they either strongly agree (n=20) or agree (n=25) with the question.

Most of the comments were related to the planet and its wellbeing, as well as the wellbeing of the people living:

> Help conserve our planet.

> It could help save the planet.

> If it could help save the planet, then why not.

> The way to save the world from global warming.

> Improve lifestyles.

> If we plan continuing to survive on this planet.

One student commented:

> It is essential.

Q6. Do you feel that future employers will require you to have knowledge of green chemistry?

There was a slight polarisation in response to this question. However, the majority of the students either strongly agreed (n=13) or agreed (n=19) that they would be required to know about green chemistry.

There were some references made to how it would benefit the companies that the students may work for in the future:

> Most companies will be up for it because it will help their business.

> A lot of industrial companies are going eco-friendly, plus for them making profit is important, so if you have got knowledge on green chemistry then probably yes.

Three students although not entirely sure whether employers would want them to know about green chemistry, showed their support for it being made something that is required:

> If they don't, they should.

> I don't think so, but I believe it should be made main topic.

> Hopefully in the future, employers will be supportive of green chemistry.

One student commented on green chemistry, not just in the context of what employers require:

> We have loads to do to save the planet, hence everyone should know about this.

One student expressed their concern over not knowing much about the subject:

> I hope not, as I won't get a job.

Q7. Do you think green chemistry can work?

There was only one response to this question that showed that the student did not think green chemistry could work. Most of the group either strongly agreed (n=10) or agreed (n=25) that it can work.

One of the main themes within the comments was based around people and working together:

> If everyone works together without ignorance!
>
> If everyone takes part.
>
> Only if we ALL work together at it.

Money was also present as a theme:

> But it does not benefit financially.
>
> As long as the methods are cost effective.

Q8. Would you like to learn more about green chemistry?

An overwhelmingly positive response was that seventy eight percent (n=39) of the students asked, indicated that they would like to learn more about green chemistry.

Some students expressed how they thought it was important to learn about it:

> I believe that it is important and that I do not know enough about it.
>
> It should be mandatory.

Students related learning green chemistry to a wider picture and not just their education, were three references made to the environment:

> Ways to help the environment.
>
> Can help have a cleaner environment.
>
> It would be great if we could learn how green chemistry could improve the environment and make manufacturing less harmful.

One student showed negativity towards the subject and seemed to disregard it as perhaps a waste of time as they believed it was just ‘common sense’:

> It’s not that hard, common sense, creating eco-friendly products. (I did that when I was six.)

In some respects this student does have a valid point, especially regarding things such as toxic waste being put down the sink. However, if it was just common sense, then students would already be practising this and there would not be a need to teach sustainability and environmental responsibility as part of the existing curriculum.

	Yes		No		Total
Question	N	%	N	%	
Q9. Are you aware of the 12 green principles?	0	0	51	100	51

Table 2.10 Summary of results from questionnaire to First Year Chemistry students

Q9. Are you aware of the twelve green principles?

Of the fifty one students that answered this question, one hundred percent answered no. This is not a surprising outcome as the principles are specific to only the area of green chemistry.

Q10. What do you think the advantages of using green chemistry are?

Thirty nine students responded to this question. The environment and pollution were prominent themes present in the comments made by the group.

There were eleven comments associated with the environmental theme, some of which were:

> Safer, cleaner environment.
>
> Making alternative forms of energy and retaining the environment.
>
> To protect the environment from being affected.
>
> Good for the environment.

Also linked to this was a theme of saving the planet:

> Save the planet!
>
> Preservation of the planet.
>
> It helps save the world and reduce global warming.
>
> Helping make a difference to 'heal the world.'

Seven students believed that an advantage of using green chemistry was that pollution could be reduced:

> Less pollution in rivers so more food because the fish won't die.
>
> Less pollution.
>
> Less pollution, i.e. less toxic products, as they are recycled.

Global warming and carbon emissions were also common amongst the comments:

> Less CO_2, deter global warming.
>
> Reduces global warming, less carbon footprints.
>
> A reduction in greenhouse gases and an eventual lowering of costs.

Q11. What do you think the disadvantages of using green chemistry are?

Thirty four students responded to this question. Seventeen of the students believed that cost was one of the main disadvantages of using green chemistry. A few students commented that it could be difficult to change to new ways of working:

> Have to generate new ways to do things differently, this may be hard.
>
> Difficult for everyone to follow.
>
> New methods, cost, skills, training.

Some students also believed that it could be too time consuming to use new methods and adopt a new way of working:

> Too time consuming, people aren't likely to follow it.
>
> Too time consuming!
>
> Cost, time.

This could signify that when this is first introduced it should be made as simple as possible to ensure that people do adopt new methods and best practise.

Q12. Do you think that the world has environmental problems?

Forty nine out of the fifty three students responded to this question. Of these students ninety four percent (n=46) believe that the world does have environmental problems. Three of the group weren't sure with comments such as:

> Kind of, I am confused due to conflicting reports about the environment.
>
> Possibly, everyone makes their judgement according to what is in the media.
>
> So I'm told.

Other comments were related to issues currently taking place in the environment:

> Yes many causing global warming and destroying the ozone layer.
>
> Yes weather problems, too much rain.
>
> Yes, too many! Climate change is affecting not only us but everyone/thing around the world.

Q.13 How do you think environmental problems may be solved?

When asked how the students thought environmental problems might be solved, forty four (n=44) responded. Five (n=5) of the students reported that they did not think that they can be solved, however, some did still comment on some things that could improve the situation:

> I don't think they can, but they can be slowed down.
>
> I'm not sure about solving them, they're at a stage where it's incurable. However, reducing the effect of these problems is possible if we act now!
>
> They can't be solved but they can be reduced by recycling, renewable energy etc.

There was a great positivity shown towards education, passing on knowledge and green chemistry as potential ways to solve these problems:

> Applying such systems as green chemistry.
>
> Through educating people.
>
> Teach the younger generation how to be eco-friendly.
>
> By Green Chemistry.
>
> More people studying green chemistry.

Changing general everyday things were also common responses:

By making everyone recycle. Cutting down on gas and fuel usage- toxic emission.

Everyone do something small that will eventually solve the bigger problem, for example, recycling.

By being generally more renewable.

Renewable energy, recycling and reusing.

People making the effort to make beneficial changes in their routines.

	SA		A		NSF		D		SD		Total
Question	N	%	N	%	N	%	N	%	N	%	
Q14. As a scientist do you feel that you have a responsibility to be green?	13	25	27	53	9	18	2	4	0	0	51

Table 2.11 Summary of results from questionnaire to First Year Chemistry students

Q14. As a scientist do you feel that you have a responsibility to be green?

There was very a positive response to this question with only two out of fifty one students disagreeing with this issue. This was very encouraging as it could mean that the introduction of green chemistry to the chemistry courses could be taken on board well.

In contrast to this, there was some negativity shown when one student commented:

Got better things to do, I mean I'm doing my part as a human being, a scientist's work is more important.

This student seems to be regarding green chemistry as an entirely separate entity to the work that he or she is already doing as part of their degree. This student does not recognise any importance of this subject and perhaps believes that it doesn't concern their work, however it should be common practise and best practise to ensure that their work does not cause an impact on environments outside of the laboratory area.

There was a lack of qualitative comments left, however one student showed their full support through the following:

> As a scientist and fellow human being.

Q15. How can we be more responsible in the lab?

Forty eight (n=48) students responded to this question. The most common responses were concerned with waste and the disposal of chemicals. Fifty percent (n=24) of the students thought that improving the way that chemicals are used during and dealt with post experiment would be the first step to becoming more responsible. Comments included:

> Less waste of chemicals would be a start.

> Avoid wasting chemicals.

> Make sure waste products are disposed of properly.

> Reuse stuff, less waste.

Of these comments, there were some students that recognised how much waste can end up by being disposed of down the sink:

> Don't be wasting products and putting chemicals down the sink, also acetone used.

> Not wasting a lot of products. After using certain chemicals dispose of them in a waste jar or bottle instead of the sink.

> Better management of chemical waste. We put way too much chemical waste down the sink.

Not wasting chemicals or pouring damaging ones down the sink.

Using and generating less harmful chemicals and using these in smaller quantities was also a popular response:

Doing experiments with less pollution and producing less harmful gases and products.

Using harmful chemicals in the minimum quantity.

Do reactions producing less harmful products etc.

Use less dangerous solvents and elements.

There were three references to working in pairs rather than alone.

	Yes		No		Total
Question	N	%	N	%	
Q16. Do you routinely design your own experiments?	3	6	49	94	52

Table 2.12 Summary of results from questionnaire to First Year Chemistry students

Q16. Do you routinely design your own experiments?

Ninety four percent (n=49) of the students who responded (n=52) reported that they do not routinely design their own experiments. This was expected due to the stage that the students are currently at in their university careers.

Question	SA		A		NSF		D		SD		Total
	N	%	N	%	N	%	N	%	N	%	
Q17. Do you look for using alternative, more sustainable reagents?	3	6	7	14	25	49	14	27	2	4	51
Q18. Do you consider why you are using a certain reagent or solvent?	2	3	17	33	14	27	14	27	5	10	52
Q19. Do you consider how much washing solvent you use?	2	4	16	29	13	25	18	34	4	8	53
Q20. Do you use correct chemical disposal routes?	16	30	23	43	6	11	8	16	0	0	53
Q21. Would you be prepared to change your current lab practise in order to incorporate green chemistry?	14	27	30	59	7	14	0	0	0	0	51

Table 2.13 Summary of results from questionnaire to First Year Chemistry students

Q17. Do you look for using alternative, more sustainable reagents?

When asked this question there was quite a polarisation in response. The majority of students (n=25) responded with no strong feeling, however sixteen (n=16) reported that they do not consider alternatives, which was more than those reporting that they do.

Some comments made by the students seemed to suggest that they don't feel as though they have this as an option:

> I don't think I'm old enough to be making these decisions.
>
> I don't have a choice.

> We as students don't have a say.

One student seemed to misunderstand what an alternative reagent meant:

> What's the point, if it's not going to create the product you want, why use it in the first place?

A reagent would be substituted for an alternative that would give the same product but could be less harmful, produce less by-products but still give the desired product. The 'what's the point?' attitude to this issue is one that can be a hindrance to the introduction of green chemistry and this opinion must be changed by showing the benefits.

One student commented:

> Wouldn't know where to start.

As these students are at the beginning of their university courses, it would be expected that they might not have enough knowledge of chemistry to be able to do this, however with more experience students could begin to do this.

Q18. Do you know the function of the reagent that you are using and the part that it plays in your reaction?

This question showed a great polarisation in response and there was no clear definition between those who do and do not know the function of the reagent that they are using. The comments were also quite varied.

Two students commented on the lab scripts given in their practical classes:

> I just follow the script!

> It's explained in the lab script.

It was expected that the majority of students may have the former response. The lab scripts used by the students do not usually contain the functions of the reagents used so it could be that the student that gave the latter comment misunderstood the question.

Two students were keen to show that they do know the function:

> Yes, otherwise you're not a chemist.
>
> I try to work it out.

Q19. Do you consider how much washing solvent you use?

The response for this question was mixed once again, the majority of the students either disagreed (n=18) or strongly disagreed (n=4) that they consider how much is used. It was expected that the majority of the students would respond in this way as washing solvents generally made freely available for students to use and are usually not informed of how much is a suitable amount to use.

There were comments related to using too much washing solvent:

> Probably too much to mention.
>
> In the lab we get forced to clean the equipment with a lot of washing solvent. Plus the professors use two bottles of acetone to wash a 250cm^3 conical flask.

In contrast to this, some students commented on using an appropriate amount of washing solvent:

> Try not to use too much.
>
> Not much is used as the amount available is limited.
>
> Just to wash the walls of the flask.

Q20. Do you use correct chemical disposal routes?

There was an overwhelmingly positive response to this question with seventy four percent (n=39) of the students either strongly agreeing (n=16) or agreeing (n=23) that they do use correct disposal routes. It was expected that this number would have been slightly lower due to the comments that the students made in relation to question fifteen- how can we be more responsible in the lab, with the main responses being associated with correct waste disposal and waste management. However, the students may think that this can be improved from what they are currently doing, by the university providing better ways to dispose of waste. This is reflected in one of the comments made by the students:

> I do the best I can but I think the university should manage waste better.

There was also evidence that some students have paid attention to the information that they have been given in laboratory classes with comments such as:

> For example, don't throw nickel down the sink as it leads to fish dying.

One student commented:

> I dispose of things according to instructions.

Q21. Would you be prepared to change your current lab practise in order to incorporate green chemistry?

There was again, an overwhelmingly positive response from the students, with eighty six percent (n=44) indicating that they would be prepared to change their lab practise. There were no responses showing that students would disagree with the introduction of this. There was a lack of comments left in regards to this question.

Question	Yes N	Yes %	No N	No %	Total
Q22. Are you aware of current chemical legislation?	3	6	48	94	51
Q23. Have you heard of REACH?	5	10	46	90	51

Table 2.14 Summary of results from questionnaire to First Year Chemistry students

Q22. Are you aware of current chemical legislation?

Ninety four percent (n=48) of the students were not aware of current chemical legislation.

Q23. Have you heard of REACH?

Ninety percent (n=46) had not heard of REACH. These results conflicted slightly with the results of question twenty two as REACH is a form of chemical legislation, students may have misinterpreted this question or not made the link between the two.

2.5.3 Summary of findings of student perception study

The data collected has given a rich insight into how the MSc Analytical Sciences and First Year Chemistry students view green chemistry, sustainability and their current laboratory practise. Overall the information obtained from both the MSc Analytical Sciences and first year Chemistry students was extremely positive in terms of improving laboratories and introducing a green chemistry and sustainability component to the course. Comparison of the results from both the questionnaires and observational studies did not show any significant differences between the ways that the students think about green chemistry and sustainability when just entering higher education and entering postgraduate education, and similar themes were present in both forms of data collection.

This study also showed the benefit of using a multi-method approach. Using just a questionnaire as a source of data from the students would have resulted in the loss of valuable data and such a rich insight into the experiences of the students at the university studying within the chemistry department. The use of participant observation provided an additional means of tapping into the student experience and allowed the students to emphasise and bring points to attention that they believed to be important issues.

The comments given have shown that the students are willing to take this ‘new form of chemistry’ on board as part of their course, without this qualitative research, it would not be known how it would be accepted. The observation was useful as the students made comments on their observations of their current practise and the laboratory environment in which they work in, these along with suggestions for improvement may have otherwise been overlooked by the academic or technical teams, but have now been brought to attention. Mention of knowledge gained through experiences at other institutions and workplaces was also brought to attention, giving good starting points for how to embed this aspect of chemistry into the courses successfully, and of enabling the laboratory classes and laboratories themselves to be changed for the better.

There were a large number of suggestions made by the students to improve the laboratory environment; these were mainly within the area of better waste management. This is in terms of a better system of disposing of hazardous waste; the students had recognised how a suitable system is not in place at present and showed concern over this.

In terms of the laboratory classes, it would be useful for students to understand how the reagents they are using function in their experiment, this could give them a starting point for suggesting greener alternatives when they gain more experience within chemistry. Students also stressed on more than one occasion that they are not always aware of the hazards of the chemicals that they are using and the potential they have to make an impact if they were to be released into the environment *via* drains etc. As a potential solution to this, a way to implement best practise, and in preparation for students going into industry, the students could be asked to fill in COSHH forms with an environmental component to them, enabling them to see the hazards to themselves and the environment. The use of these activities could perhaps convince students to question what they are doing in terms of the methods and reagents that they are using and deter them from 'just following the script!'

In relation to housekeeping in the laboratory and following best practise, the first year students suggested a pre-lab session that shows new students best practise and how they can carry out their work without making such a large impact on the environment. An example of this is, when cleaning glassware teaching the class that they do not need to use excessive and unnecessary amounts of solvent, which ultimately go down the drain and into the environment.

The first year students in particular, were keen to see the introduction of green chemistry to their modules, they emphasised how they would like to learn more about current green chemistry issues, and the theory to work out how to potentially solve them. This however must be paired with the application of the theory, as some students stressed how they thought it would work best having green chemistry taught from a theoretical point of view and the chance to apply it in the laboratory.

CHAPTER THREE: Potential future employer and staff perception of environmental awareness and sustainability in the chemistry curriculum

3.0 Introduction

This chapter details the perceptions that staff and employers have of environmental awareness and sustainability in the curriculum, in terms of the integration into the chemistry syllabus and what employers expect from graduates. The work carried out was primarily small-scale pragmatic research with a view to explore these perceptions and gain a feel for what these people think about the ideas of environmental awareness and integration into the curriculum to inform curriculum development.

3.1 Introduction to employer perception study

The Chemical and Forensic Sciences department at the University of Bradford possesses a high reputation for graduate employability. In 2008, 88% of students either went on to further study or into employment within six months. The Royal Society of Chemistry recently carried out a survey of graduate destinations and discovered that the majority of students that go into employment either go into work within industry or commerce. [63]

The chemistry programmes available at the university offer integrated placement years to students who wish to gain experience and apply the knowledge that they have acquired through their course to a job within the chemical industry. As the chemistry courses at the university possess strong links with companies through these placement years, it was felt that a needs analysis of them as potential future employers should be carried out to find out what they require from chemistry graduates seeking a job within the chemical industry. This will potentially allow the curriculum to be shaped in the best way to give Bradford students an edge when looking for employment.

3.2 Aims of potential future employer study

The main aim of this part of the study was to gain the relevant information from potential future employers within the chemical and related industries to shape the chemistry curriculum at Bradford to equip graduates for future practice within the chemical sciences. It was also important to understand how the industry is switching to more sustainable practice due to legislation, and how they had made this transition. This required gathering data regarding the following:

- How recent legislation such as REACH (The Registration, Evaluation and Authorisation of Chemicals) has affected the chemical industry, to what extent and within which areas
- Whether they currently use sustainable laboratory practise and if so, how and where
- What they expect from graduates, whether having a background in green chemistry would benefit them and how important they view the need for students with it
- Which areas within green chemistry and sustainability they believe students should be aware of in order to work in the chemical industry

3.3 Data Collection Plan

3.3.1 Method of data collection for staff and company perceptions

The data collected from staff and employers was carried out using the same methodology and as a result the following applies to both studies. After a literature search using internet search engines and databases such as Web of Knowledge and Scifinder, it was clear that there was no evidence to suggest that this type of data had been collected by any other institutions, therefore qualitative research provides this opportunity. [38] To collect the required data, telephone (in the case of companies) and where possible face-to-face interviews were conducted, respondents were also given the option to take part in the study by answering the same questions *via* a questionnaire. Questionnaires are another well known method for carrying out surveys (refer to Chapter Two for critique of this method); however research has shown that taking an interview method of data collection gives a higher response rate due to the accessibility of the participant within the survey. [43] Further information and a critique of this data collection method are offered in a later section.

Although this did not form the basis of a multiple data collection approach it was not felt that it was appropriate for this study as the responses would be straight to the point about what the companies look for and how they currently practice sustainability, this study was more about exploring the employer perceptions of these issues through small scale pragmatic research. This was also applicable to the staff perception study.

The companies and staff were first contacted *via* email with an attachment containing a questionnaire (refer to Appendices C and D for questionnaires) and were given a brief introduction to the work that was being carried out at the university which put the study into context. Companies and staff that agreed to take part in the survey were given the option of either taking part by filling in the attached questionnaire or participating in a telephone interview (or face to face for staff) in which exactly the same questions were asked in the form of an interview schedule. This was used in an attempt to raise the response rate as high as possible in the case of participants that may be discouraged from taking part in the survey due to not feeling comfortable in an interview situation.

The data was collected in note form. This did not pose a problem as a suitable rapport was built up with the interviewee, which meant that they were aware that what they were saying was being transcribed and that there may be small gaps within the interview whilst what they had said had been noted. Another option was to record and transcribe the conversations after the interview had taken place however this can bring extra ethical issues into consideration. Written approval is often sought before the interview can take place, and failing that, the participant must confirm their name and that they have no objection to being recorded when the interview takes place. After the interview has taken place there are also issues regarding the timings when the recordings must be disposed of *etc*. [64] The nature of this subject may also have influenced whether individuals would be prepared to be audio-recorded, therefore note form seemed the simplest way to record the data in this situation.

3.3.1.1 Telephone surveys and interviewing as a data collection method

Interviews are divided into categories depending on their structure. A fully structured interview uses questions that are decided precisely in advance, with set wording and are usually in a pre-set order. This structured approach allows easy comparison between respondent data, but may not elicit as much information as an unstructured interview. Unstructured interviews involve the interviewer being given a subject in broad terms and it is up to them to elicit the information in any way that they see fit. At the interface of these two categories is the semi-structured interview which uses predetermined questions but the wording and order of the questions can be modified if the interviewer feels that it is required. [65]

A short, semi-structured interview was used for this study as it allowed the omission or addition of questions and gave more freedom to find out more during the interview by asking more if extra information seemed available. The wording of the main questions remained exactly the same for each participant and it was only when asked to expand on the areas that they had mentioned that the addition of more questions was used to prompt them to give more information and to act as a probe. Interviewing gives this opportunity to delve deeper into a response given by an interview. [66] A probe is a device used by interviewers when they feel that an interviewee may be able to expand on the response that they have given. This was useful when interviewees were asked to give examples for the questions that they had answered. Obvious probes such as, 'Is there anything else you can think of?' and leaving a period of silence prompting the interviewee to expand on what they have said to fill the silence, were used within this study. [59, 67]

This form of interviewing also allowed explanations to be given to questions in the case that a participant did not fully understand what the question was asking, however this was not required.

Interviews as a data collection method present a number of advantages and disadvantages. This type of data collection offers a flexible and adaptable way of finding things out. However, a number of research textbooks comment on how this method can be extremely time consuming in terms of the interview itself and preparation- making arrangements, confirming arrangements with participants *etc*. [43, 68] As long as time budgeting is used within a project this is said to pose less of a problem.

Prompts can also be used, similar to those used in a questionnaire; an interview can suggest to the interviewee a range of possible responses. [59] In this study a lickert scale [42] which allowed the participants to give their agreement or disagreement with a statement on a scale, was used with the majority of questions to facilitate easy comparison between the results of the survey and to allow the data to be presented comprehensively.

Interviews carried out through telephone surveys were chosen also due to their relatively high response rates. Gray comments on how response rates for telephone surveys are usually between 60-90 per cent when repeated call backs are made. With the multiple communication approach- email and telephone, participants were also inclined to take part in the survey. [42] Armstrong *et al*. had also commented on how they used short, structured interviews as a means of accessing GPs to ask their views on NHS changes and how they recognised the method as an efficient tool for chasing non responders. [69] In contrast to a solely postal questionnaire method, this way also allows the researcher to convince people of the significance of the research that they are carrying out and how their response is highly valued, it also allows them to reschedule for a time that suits the participant best. High response rates are highly desirable within studies to facilitate the collection of data rich in evidence and this study was no different.

One limitation of telephone interviews is the type of questions that can be asked, the questions must be short, simple and easy to understand and the kinds of response choices should be kept few and short. The sentences should also be limited to approximately twenty words and the language should remain as simple as possible. [59] To make it easier for the participants in this survey, the questions were sent to them in order to allow them to familiarise themselves with the questions before the interview took place.

To ensure that the information gathered is able to be compared easily, it is essential that the interviewer remains consistent. [42] For this reason an interview schedule was used to keep the interview on track and so that each participant in the survey encountered the same experience.

3.3.2 Participants of the employer perception study

This study targeted a wide selection of companies within the chemical industry and related industries such as the pharmaceutical and personal care industries and involved those that students often work for during their placement years. The companies targeted were both UK based and global. The sample ranged from very large and widely respected pharmaceutical companies such as GlaxoSmithKline, also a leader in sustainability innovation, Dr Reddy's Pharmaceutical Company and Novartis, to agrochemical producers such as Nufarm. And smaller independent companies such as Crystec Pharma, who provide the pharmaceutical industry with crystal and particle engineering solutions, Lena Nanoceutics who are focused on the development of improved formulation processes for prescription drugs, over the counter medicines and healthcare products and Microsearch Laboratories Ltd providing specialist analytical chemistry and microbiology services to the food industry.

3.3.3 Response rates: employer study

A total of twelve (n=12) companies were contacted in order to gain a feel for what is currently happening in terms of environmental awareness and sustainability within the chemical and related industries and to find out what employers expect from graduates. These companies were chosen as they were places that Bradford students had taken employment with in the past. The response rate was fifty eight percent (n=7). After various phone calls, the response rate improved slightly however it was still not possible to achieve a one hundred percent response as some companies did not show an interest in participating in the study which could be due to the nature of the study meaning that they did not want to disclose information about how their company is currently dealing with legislation and the need for sustainable practice.

3.4 Findings of the employer perception study

The following section details the findings of the responses received from companies through filling out the questionnaire or participating in a telephone interview in which exactly the same questions were asked. In some cases some companies did not answer all questions. To begin the questionnaire/interview companies were presented with statements for which they responded by the use of a scaled response, the table below shows the responses received. The following is the notation used within the table of these results:

SA = Strongly agree A = Agree

NSF = No Strong Feeling

D = Disagree SD = Strongly Disagree

	SA		A		NSF		D		SD		Total
Statement	N	%	N	%	N	%	N	%	N	%	
1. The recent introduction of REACH legislation (The Registration, Evaluation and Authorisation of Chemicals) has had a major effect on our company	1	14	2	29	0	0	3	43	1	14	7
2. Legislation such as REACH will become more important in the future	0	0	6	86	1	14	0	0	0	0	7
3. An assessment of environmental impact is included within risk assessments	1	14	2	29	2	29	2	29	0	0	7
4. Our company practises sustainable laboratory practise (examples: safer alternatives, waste reduction)	0	0	4	58	1	14	1	14	1	14	7
5. Our company foresees difficulties with switching to sustainable laboratory practise	0	0	4	58	0	0	3	42	0	0	7
6. There were problems when switching to sustainable laboratory practise	0	0	1	33	2	67	0	0	0	0	3
7. Our company uses metrics as a tool for assessing and monitoring how green our chemical processes are	1	14	0	0	2	29	0	0	4	57	7
8. Our company looks for graduates with an understanding of green chemistry and sustainability	0	0	3	43	0	0	4	57	0	0	7
9. It would be beneficial to our company to employ chemistry graduates with knowledge and understanding of green chemistry and sustainability	0	0	6	86	0	0	1	14	0	0	7

Table 3.1 The findings of the scaled response questions from employer interviews

Q1. The recent introduction of REACH legislation (The Registration, Evaluation and Authorisation of Chemicals) has had a major effect on our company

There was a polarisation in response to this statement, with three companies strongly agreeing (n=1) or agreeing (n=2) that the introduction of REACH legislation has had a major effect and four companies strongly disagreeing (n=1) or disagreeing (n=3). The legislation appears to have had a strong effect on larger companies but is yet to cascade down into smaller companies where they have encountered a minimum effect. The areas that had been mentioned as being affected were mainly within procurement and production. The following comments show how REACH legislation has driven companies to make changes:

> It has mostly affected production, we have dedicated REACH employers for the products that go through REACH. Our research labs are racing against time to re work products to replace those that will be phased out by REACH.

> Procurement area, understanding what we're buying and where it's coming from. The industry must comply with laws- making sure that they're not breaking any and get it right.

Q2. Legislation such as REACH will become more important in the future

The vast majority of the sample (n=6) believed that legislation such as REACH will become more and more important. The participants suggested reasons related to need for the use of less toxic and more environmentally friendly chemicals and the need to look for alternative methods that comply with the legislation. One company commented on how this legislation causes a nervous atmosphere among suppliers:

> We're tightening up in the chemical industry, this makes suppliers nervous and this impacts on us.

Tightening up of legislation around regions of the world was also a reason why one company believed REACH would become more important:

> It will continue to get tougher as legislation around regions of the world is toughened.

Q3. An assessment of environmental impact is included within risk assessments

There was a polarisation in response to this statement, however more participants agreed with this statement than disagreed. Two companies commented on how environmental impacts are a high concern for them:

> We use an environmental process review for chemical manufacture. For formulation activities we carry out an environmental impact assessment of pharmaceuticals and look at waste flows. We are very concerned about environmental impacts.

> Damage to the environment is a major concern for this company.

The companies indicating that they do not include a full environmental impact assessment as part of risk assessments commented on how they do try to reduce environmental impact by managing chemical waste in the correct way.

Q4. Our company uses sustainable laboratory practice

There was polarisation in response to this statement, however the majority (n=4) of the participants agreed that they do use sustainable laboratory practice. This was demonstrated through examples concerning the use of alternative solvents and reagents:

> We only use and generate carbon dioxide through the use of supercritical fluids for the recrystallisation work that we carry out. The carbon dioxide that we use is a by-product if the food industry which would have been released to the environment anyway. By using this technology we are reducing the use of other solvents.

> As part of the safety policy the safest alternatives are always chosen.

> We have been trying to influence and educate in this area for ten to fifteen years and are now leaders in the industry. Our solvent guides turned the corner.

Q5. Our company foresees difficulties with switching to sustainable laboratory practice

There was a polarisation in response once again with the majority (n=4) agreeing that they foresee difficulties with switching to sustainable laboratory practice. The reasons given for this were associated with cost, motivation and conflicting business targets. The following quotes show examples of these themes:

> There are some issues with motivating people to change their current practice. Also costs- some companies recycle their HPLC effluents, we don't here and people don't want to due to the hard work. It costs more to recycle so there is no benefit cost wise.

> Finding alternatives that work with the current methods may cause an issue. If we have to change a method, we may need new equipment which could result in being very expensive.

> You might want to be sustainable but there are real world time constraints that limit this, as in this industry products must be delivered on time, this leaves less time to search for alternatives.

On the other hand some companies showed how they were not concerned about switching to more sustainable laboratory practice as they felt that it would not affect them too greatly due to the nature of the chemicals that they use or they had already begun making changes and had not encountered any difficulty.

Q6. There were problems when switching to sustainable laboratory practice

Three companies (n=3) responded to this question as the other thought of it as being non applicable to them. One response (n=1) indicated agree and two responses (n=2) indicated no strong feeling. The only comment given was related to conflicting business targets and time constraints as seen in the previous question.

Q7. Our company uses metrics as a tool for assessing and monitoring how green our chemical processes are

One company responded to this question, strongly agreeing that metrics are used as a way of monitoring their chemical processes in research and development and manufacturing, they also indicated that mass intensity is a main metric used.

The remaining participants either responded with no strong feeling (n=2) or strongly disagree (n=4). Those that strongly disagreed were either not fully aware of them, or indicated that they may not be applicable to the type of work that they carry out, however some companies did express how they may be a useful tool to use:

> We don’t currently have anything like this in place, it may also not be applicable to the work that we’re carrying out, but would be a good idea to keep track of impact.
>
> Could be something to think about in the future if legislation requires it.

Q8. Our company looks for graduates with an understanding of green chemistry and sustainability

There was a polarisation in response once again, with three participants agreeing (n=3) and four disagreeing (n=4) that they look for graduates with an understanding of green chemistry and sustainability.

Those disagreeing expressed how they preferred chemists that are good at what they do that can pick up knowledge through their job, they also stated how they have no preference and that it is not a requirement. The following quotes give examples of this:

> It is important to train them to how they need to be for the job role and to see the ability of them to adapt to specialist areas. We want them to take knowledge and use it; they come as an empty shell and build on it to become specialists in their field.

> We look for outstanding chemists.

> It is not a requirement but it could be beneficial.

One company agreeing expressed how they would not expect a huge knowledge, but expect students to know how to work safely and responsibly in the laboratory. Another company expressed how it is often something that is used as a talking point in interviewing candidates for jobs within their research and development department.

Q9. It would be beneficial to our company to employ chemistry graduates with knowledge and understanding of green chemistry and sustainability

The majority (n=6) of the participants agreed that graduates with knowledge of green chemistry and sustainability would be beneficial to them. Some reasons for this were related to good practice in the laboratory:

> Good lab practice- good company reputation.

> So they already have an understanding in terms of correct waste disposal and good practice in the lab.

Reasons were also related to how it would be a good add on to the knowledge graduates would have from the core chemistry learned through their course:

> It depends on the job- for an analytical job, analytical skills and techniques would come first and then green issues secondary as a nice add on.

> It must be an add on to the key skills that groups within the companies want. Want a chemist, not just a green chemist. Should be embedded into the curriculum I think.

It was interesting how one company expressed how they thought that green chemistry and sustainability should be embedded into the curriculum, and a positive output to show that the aims of this project to embed was something that some companies also think is the way to do it.

Two companies expressed how graduates with this knowledge are important in terms of advising the company and understanding the importance of green issues:

> Hiring someone who is competent and understand the importance of green chemistry is a major asset to the company.

> They could advise on ways to improve the sustainability here as there is currently no one employed to do this.

In relation to the last quote, if graduates can have enough knowledge to advise companies of best laboratory practice and alternatives etc, it is possible that this could give them an edge over other graduates.

The company disagreeing with this statement was more concerned of students having a wide knowledge but would like them to be aware of these issues:

> Just have an awareness. It is important for them to have a wide view of the world and a wide awareness of a lot of different areas of interest.

Q10. On a scale of 0 to 10, how important do you rate the need for graduates with knowledge and understanding of green chemistry and sustainability? (0 = not at all important, 10 = very high importance) What are your reasons for your choice?

On average the companies rated the need to graduates with a knowledge and understanding of green chemistry at 6.5. (0 = not at all important, 10 = extremely important) The basic response was that although it is important, it is more important to be good at the job that they are employed to do. The following comments expressed their reasons:

> We want a whole rounded person, but also want them to know what's going on now and in the future so that the company can be ahead of the game as the chemical industry is a very fast moving environment to work in, especially with the innovation and research in places like China.

> Good to have knowledge and important for the future but it doesn't mean that they will be good at their job. For example, if they went for a job in quality control, just because they know about green chemistry and sustainability it doesn't mean that they will be any good at their job.

> Knowledge of this topic is important but it is not what is needed to get you a job here.

Q11. Are there any specific areas of green chemistry and sustainability that you think students should be aware of in order to work in the chemical industry?

Companies believed that students should have an awareness of the following areas of green chemistry: Renewable resources, legislation, why green chemistry is important and beneficial to the industrial sector. One company believed that having a basic knowledge of industrial chemistry may prepare graduates for employment within the chemical industry. In terms of laboratory practice, companies believed students should be aware and competent with best practice such as waste management, chemical handling, toxicity of materials, alternatives, consequences of the choices that students make in the lab, environmental impact in terms of their experiments and energy conservation.

3.5 Introduction to staff perception of the introduction of environmental awareness and sustainability into the chemistry curriculum

In 2008 the chemical and forensic department at the University of Bradford re-launched chemistry by introducing a fourth phase of chemistry teaching into the university known as the Chemistry4 programme. This innovative chemistry provision was designed in response to graduate employer needs in the 21st century. The curriculum is still in its development stages which provided an excellent opportunity to integrate environmental awareness and sustainability into the existing chemistry curriculum.

The presence of the Ecoversity Programme within the university has also encouraged the incorporation of environmental awareness and sustainability throughout the entire institution, meaning that all curricula, regardless of discipline, must be modified to include this material. In terms of chemistry, the practical component of the course seemed an obvious choice to begin to integrate and develop sustainable practice and behaviours, due to the nature of the work undertaken and the perceived effects that practising chemistry has on the environment.

In order to successfully incorporate environmental awareness and sustainability into the existing chemistry curriculum, there is a need for staff willingness, which involves both academics and technical staff. As detailed in Chapter One, one of the barriers to this incorporation is often perceived irrelevance by academic staff. As a result of this it was important to explore the staff perceptions of the incorporation of environmental awareness and sustainability into the chemistry curriculum and related issues, in this institution.

3.6 Aims of staff perception study

The main aim of this study was to gain the relevant information from academic and technical staff within the Chemical and Forensic Sciences department to allow the integration of green chemistry and sustainability to be carried out in the smoothest way possible and to reduce disruption caused by the curriculum changes. It was also important to gain an insight into how much the staff already knew about green chemistry and whether they practice it themselves. This required gathering data regarding the following:

- Views on embedding green chemistry into the curriculum
- How and when (which stage of the course) staff think it should be embedded into practical modules
- Perceived benefits of teaching green chemistry
- Perceived barriers to the incorporation of green chemistry and sustainability into the curriculum
- How much staff already know about green chemistry, sustainability and environmental responsibility

3.7 Data Collection Plan

3.7.1 Data Collection

Data was collected in using the same methods as those used to gather data from employers (See data collection plan Section 3.3) however face-to-face interviews were used instead of telephone interviews.

3.7.2 Participants of the study

Academic and technical staff who currently teach/work within chemistry were invited to take part in this study. The chemistry department at the University of Bradford is relatively small in terms of the number of staff in comparison to other institutions. Fourteen individuals (N=14) were contacted.

3.7.3 Response rates

As already mentioned fourteen staff (n=14) within the chemistry department were contacted which resulted in a response rate of sixty four percent (n=9). After various emails and asking face-to-face, some staff still did not show an interest in taking part, some expressing that they were too busy.

3.8 Findings of staff perception study

The following section details the findings of the responses received from staff within the chemistry department at the University of Bradford. These responses were obtained through filling out the questionnaire or participating in a face-to-face interview in which exactly the same questions were asked. In some cases some staff did not answer all questions.

Q1. As part of Ecoversity in the university, one of the main aims is to embed sustainability into the existing chemistry curriculum. What are your views on this?

Of the nine participants (n=9) eight (n=8) responses showed positivity towards the idea of embedding sustainability into the existing chemistry curriculum. These responses were mostly centred around how important it is for students to understand the issues and that there is a need for this within the current curriculum. Examples of this include the following quotes:

> Important for the future development in the sciences, and is therefore important that it becomes a core part of the curriculum for younger scientists to learn about.
>
> An important topic to cover throughout the chemistry course. The future development of the subject must identify sustainable sources and methodologies to counter the poor existing image of chemistry and allow the subject to exist.
>
> Good idea and something that is needed, students and staff do not think enough about these issues.
>
> Important for the future.

The remaining participant did not believe that sustainability is something that should be made mandatory for students to learn about by embedding it throughout the entire curriculum.

> I don't think it should be embedded into the curriculum. It should be taught as an optional subject as it is an individual view point.

Although there was one negative view point towards this issue, the positivity shown by the other participants showed that most of the staff are willing to take this subject on as an integral part of the curriculum.

Q2. How important do you rate the need for students to be given a background and understanding of green chemistry, sustainability and environmental awareness?

All participants (n=9) rated students being given a background to these issues as important, four (n=4) of which expressed how they believed it was extremely important, with the only reason for this being given because of the introduction of new legislation.

Q3. How would you like to see sustainability embedded into practical modules?

Seven participants (n=7) responded to this question. There was a focus on the use of pre-laboratory sessions to encourage students to think about environmental impact, one suggestion was to ask students to consider a range of solvents and reagents and to choose the best one based on sustainability:

> By allowing the students a choice of solvents/reagents in pre-lab sessions and asking them to choose the best ones in a context of sustainability.

Other suggestions for the use of pre-laboratory sessions were to include issues such as life cycles of chemicals and products and considering the entire cycle from manufacture of original reagents to disposal and questions relating to the environmental impact of the chemicals that they use as well as COSHH forms.

In terms of practicing sustainability and environmental awareness in the laboratory, there were suggestions relating to using metrics, substituting for green chemistry experiments and reducing impacts by sharing equipment. The following quotes illustrate this:

> Ask students to consider metrics in their experimental work and develop green chemistry experiments which focus on developing skills.

> Students working in groups to reduce the energy impact of the large numbers of apparatus currently being used.

Q4. In which year(s) do you think this should be incorporated into the curriculum?

Out of the nine participants (n=9), six (n=6) believed that sustainability and environmental awareness should be incorporated into all years of the curriculum. The reasons for this were related to ensuring that it becomes an integral part of the students education and not seen as a bolt-on subject to the curriculum, and to emphasise the importance of it as a central skill for future science. The following quotes show evidence of this:

> Need it throughout the curriculum to emphasise the importance of green chemistry.

> All doing it this way it will become a normal part of the learning process rather than an add-on at a later date.

> Get them thinking about green issues from day one to make an integral part of chemistry as opposed to a bolt on.

The remaining participants believed that this subject should only be included in years one and two (n=1) or year two onwards (n=2), reasons for this included:

> Give them the fundamentals of chemistry first.

> In the first year it is important to focus on the development of basic skills rather than over complicating practical work with more information than necessary.

Q5. Incorporating green chemistry into existing modules rather than teaching it as a standalone subject has been suggested as the best way to teach it, are there any other ways that you would prefer to teach the subject?

Eight participants (n=8) responded to this question, seven (n=7) of which agreed that incorporation of sustainability and environmental awareness into the existing curriculum was the best approach and they would not prefer any other approach to teaching the subject. The remaining participant expressed how setting mini-projects related to this area could be something to consider.

Q6. What do you see as the benefits to teaching green/ sustainable chemistry?

A common response amongst this question was raising awareness, both in terms of raising awareness of issues related to environmental impact and sustainability and students gaining a wider understanding of why certain chemicals are used *etc* the following quotes illustrate this:

> Wider understanding of why certain chemicals are used and to get the students thinking about what materials to use rather than simply following scripts, increasing their awareness.

> A greater awareness of the use of chemicals and their impact on the environment. This would include health and safety as well as financial gains and losses. Opening up new ways to think about how traditional chemistry can be delivered in a more relevant and engaging way to students who will hopefully go on to develop the subject in the future.

Some staff also believed that it would give students an edge in terms of employability and an understanding of what is currently happening in the chemical industry:

> Gives students an awareness of these issues and improves employability prospects, industry is going down this route so the curriculum should too.

> Gives students ideas of what is happening in industry.

> An increased awareness among students will lead to an increased awareness amongst employers and companies who have the power to make the real difference.

Staff also believed that the incorporation of this subject could enhance the student experience as well as giving them insights of the skills required for future development of chemistry.

Q7. Do you see any barriers to the incorporation of green chemistry?

Out of the nine participants (n=9) one (n=1) responded to this question expressing that they did not see any barriers to the incorporation of sustainability and environmental awareness. The remaining responses were mostly related to a lack of resource and overcoming the perception that this is just a fad.

In terms of a lack of resource staff mentioned how they believed that there was a lack of staff expertise within this area and a lack of facilities within the department to allow the incorporation of new methods.

Changing the mindset of staff was something that was commonly thought of as a barrier. The following quotes illustrate this idea:

> Academics may remain old fashioned in their approach.
>
> Need to overcome the scepticism of some that this is not just another 'fad' which will pass by in time.
>
> Time, effort, staff do not see it as very important.

Q8. What would help you to include green chemistry within chemistry modules?

Seven (n=7) out of nine participants responded to this question. Staff made it clear how they would require a background to the subject to enable them to understand the relevance of sustainability and environmental awareness and therefore teach it accordingly:

> A better understanding of what green chemistry is about and its relevance in a changing world.
>
> A justification for the changes we are making would help lecturers and demonstrators understand better and therefore make it easier to teach.

Staff also commented on how they would require templates and resources that are already prepared which would make this incorporation easier and therefore encourage more to teach this, this also included audits of facilities and experiments and where they fall short.

Packages that are already available and can be adapted to different modules/practicals.

Q9. How much do you know about green chemistry?

Six (n=6) out of nine participants of the survey commented on how they do not know very much about green chemistry and sustainability. Three (n=3) commented on how they know some related to their areas of research such as ionic liquids and solvent-free synthesis and basis issues surrounding green chemistry.

3.9 Summary of findings of staff and employer perceptions

For the employer part of this study it is clear that in terms of legislation, some companies are yet to catch up, it was indicated within this survey that some companies perhaps see graduates as being able to advise companies in terms of best practice and improving sustainability. It seems that companies believe that sustainability, green chemistry and environmental awareness should be taught by embedding it into the curriculum and as an extra element to the chemistry that they learn through their degree. Companies do not consider graduates with knowledge and understanding of green chemistry and sustainability as a requirement but do see it as being beneficial to them, especially with legislation tightening up. They have also focused on the laboratory side of chemistry and possessing best practice skills in this area, which has shown that starting to embed these principles into this area of the curriculum was a good place to start.

Of the staff within the chemistry department, the majority of them have shown positivity towards the integration of sustainability and environmental responsibility into the existing curriculum and believe that it is important that this is included within chemistry education. The majority also believed that this should be embedded into all years of the courses to emphasise the importance of the subject and so that students take it on as normal practice rather than treating it as a bolt on. Staff also feel that they require more of a background to this subject to enable them to teach it effectively and the use of pre-prepared educational materials will ensure that its addition to the current curriculum runs smoothly.

CHAPTER FOUR: Green Chemistry Metrics

4.0 Introduction

A potential way to embed green chemistry into the undergraduate curriculum is to use green chemistry metrics. The use of these metrics offer a way of quantifying how green or environmentally friendly a reaction is [70] and give students an opportunity to gauge how their experiment is potentially impacting on the environment. As already mentioned in Chapter One, Klingshirn has suggested the use of pre and post lab questions relating to the atom economy metric [8] (refer to section 4.1.2) which can prompt further questions and raise awareness of issues such as waste and whether the calculated atom economy can ever be achieved and why. This method of incorporation into the curriculum also allows students to compare and contrast between reactions and potential routes to a particular compound, giving them the chance to determine which is greener and why.

It has also become apparent that large pharmaceutical companies are beginning to use green chemistry metrics, with GlaxoSmithKline in particular who have become leaders in the field, now other companies are beginning to follow suit. The use of metrics and familiarising students with them can be used to prepare students for work within these industries, potentially giving them an edge over other graduates.

This chapter details a review of the current literature concerning green chemistry metrics which has been carried out to determine which are available with the advantages and disadvantages of each and to find out whether they would be suitable for inclusion into an undergraduate curriculum. These metrics have been tested against undergraduate practicals and a new metric system has been developed.

4.1 Review of Green Chemistry Metrics

The need to invent efficient and environmentally friendly or green chemical reactions and processes is now more important and common than ever. [71] Coupled with this, to make progress in this field it is essential to measure and 'rank' the chemical reactions as quantitatively as possible by the use of Green Chemistry Metrics.

GlaxoSmithKline have proposed the following reasons for using metrics [72]:

- To enable benchmarking and as a basis for objective comparison
- To drive change
- To meet the increasing expectations from internal and external audiences to

  describe progress, and demonstrate improvement
- To be more transparent

Curzons *et al.* of GlaxoSmithKline also comments on how current thinking suggests that the best way to make a product green is to consider what is carried out in the design stages and to ensure that it has the lowest amount of adverse effects on the environment as possible, also known as the so-called, 'design for the environment' approach. Metrics can play a key role in this. [73]

It has been established that a good metric should be objective rather than subjective, clearly defined, simple and measurable. [70] Marteel *et al*. also commented that data needed for the metric should not take large amounts of time to collect and the metrics should allow for comparison of results. [74]

A number of metrics have been invented over the years, among the most described methods are Trost's atom economy [75-77], Sheldon's environmental impact (E) factor [78] and reaction mass efficiency. [73] Recent studies [71, 79] have reported that these metrics have been incorporated into reaction sequences, particularly within the pharmaceutical industry due to this area of the chemical industry being singled out as being the one producing the most waste per gram of target product. [71, 79] Although these metrics are relatively well known and have been used for some time, they have remained separate and unrelated from each other. There is still the ongoing debate as to which metric(s) are best to quantify 'greenness'. Other metrics include those such as mass intensity, mass efficiency and carbon efficiency. [80] These metrics, along with a semi-quantitative method to assess the effect of organic chemical reactions will be discussed.

4.1.1 Yield

The traditional way of evaluating the efficiency and effectiveness of a chemical synthesis is by using yield. Although this gives a good indication of how well the reaction has performed, it does not take into account the production of undesired by-products that make up an essential piece of the synthesis or energy intensive unit operations such as solvent separation or distillation etc. [13]

When yield is calculated it is only the moles of starting material versus the moles of final product which are considered. A yield of 100% could therefore signify an efficient reaction; however the reaction may produce one or two moles of waste for every one mole of product. Assessing 'greenness' using this method alone is therefore not desired, as waste and by-products are overlooked and a false result could be given.

4.1.2 Atom Economy

Atom economy is one of the most fundamental and important points of the twelve green principles. [81] Trost first described the concept of atom economy in 1991. [75,80] It is an assessment in which all the reactants are considered to the degree to which each of them is incorporated into the final product. [13] It should be noted that final product applies to a single chemical transformation, a series of chemical transformations in a single stage of a multistage synthetic route, or to the entire route to a final product. [70]

Mathematically, atom economy is calculated simply by the molecular weight of the product divided by the sum of the molecular weights of the reactants. It is a gauge of how many atoms are used up to form the final product, and how many become waste or by-products.

Atom economy for a generic reaction,

$$A + B \longrightarrow C$$

$$\text{Atom economy} = \left(\frac{\text{m.w. of product C}}{\text{m.w. of A} + \text{m.w. of B}}\right) \times 100$$

Equation 4.1 Atom economy of a given generic reaction is calculated by dividing the molecular weight of the products by the sum of the molecular weight of the reactants.

Atom economy for a generic linear process, involving a number of steps,

$$A + B \longrightarrow C$$

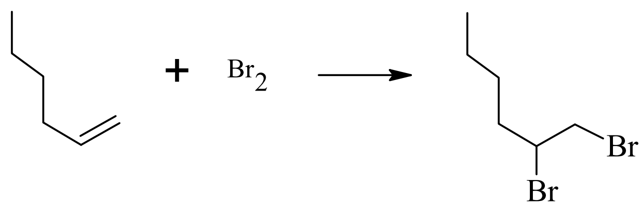
$$C + D \longrightarrow E$$

$$E + F \longrightarrow G$$

$$\text{Atom economy} = \left(\frac{\text{m.w. of product G}}{\text{m.w. of A} + \text{m.w. of B} + \text{m.w. of D} + \text{m.w. of F}} \right) \times 100$$

Equation 4.2 Atom economy calculation for a generic linear synthetic process.

An example of a 100% atom economical reaction is the addition of bromine to *n*-hexane:



Scheme 4.1 The bromination of *n*-hexane, with an atom economy of 100% as all atoms are incorporated into the final product

Although this reaction boasts a high atom economy, it should not automatically be assumed that the process is ‘green’. The reaction may require large amounts of power through heating for example, to complete. This method does address failings evident in the yield approach, however it does not address any hazards associated with the final product. For these reasons atom economy should not be used as an independent way of assessing ‘greenness’.

The main benefit of using the atom economy metric is that it can be calculated from a balanced chemical equation in the reaction planning stage. [81] This allows it to be calculated before any practical work is undertaken; therefore if there is more than one route to a particular compound the most atom economic way can be found prior to its synthesis. Lancaster describes the metric as the most useful design tool for reactions with minimum waste. [6, 81] The idea is that for environmental and economical reasons, it is desirable that reactions are atom efficient.

There are certain assumptions that must be made about the reactants, stoichiometry and resolution and purity of the chemical process to enable an accurate calculation of atom economy. [70] This allows the method of calculating atom economy to remain relatively simple. Reaction yield, solvents, other reagents and catalysts that do not form the end product are excluded from the calculation, which again ensures that it remains relatively simple.

Reaction stoichiometry is taken into account, however if an excess of reactants is used to maximise the reaction yield, this is ignored. In syntheses that use a resolution step, the reaction stoichiometry is adjusted as some of the mass will be discarded due to an unwanted enantiomer.

4.1.3 Environmental (E) Factor

Sheldon expanded the concept of atom economy by introducing E-factor in 1994 [78]. One of the most quoted studies was that carried out by Sheldon as an analysis of the waste produced as a result of the reactions and processes carried out within each industry sector, bulk chemicals, fine chemicals, pharmaceuticals. It was revealed that tens of kg of waste per kg of desired product were being produced, this led Sheldon to propose the term E factor as a metric for quickly assessing, the environmental impact of the reactions and processes being carried out. [82] Table 4.1 shows the waste production within the various sectors of the chemical industry.

Industry sector	**Volume/tons of waste per annum[a]**	**E factor (kg waste per kg of product)**
Oil refining	10^6-10^8	<0.1
Bulk chemicals	10^4-10^6	<1-5
Fine chemicals	10^2-10^4	5->50
Pharmaceuticals	10-10^3	25->100

Table 4.1 Waste and E-factors in the chemical industry. [a] Annual production of the product worldwide or at a single site. [82]

E-factor has been widely accepted in the chemical industry for quantifying waste elimination and for innovation into waste reduction, [83] especially with the increasing pressure on the industry to minimise or preferably eliminate waste in manufacturing. [84] Sheldon comments on how this metric has provided and continues to provide the drive for developing cleaner, more sustainable processes. [85] Sheldon also discusses how this metric, along with atom economy are now generally accepted as two useful measures of the (potential) environmental acceptability of chemical reactions and processes.

In mathematical terms E-factor is the ratio of waste (by-product) per kilogram of product and draws attention to the amount of waste produced for the chemical process. In this context, waste (by-product) is referred to as all materials in the synthesis excluding the final desired product, taking into account the yield and all reagents, solvent losses and process aids.[6, 85] E-factor is an output orientated indicator [86] which is relatively simple and easy to understand.

$$\text{E Factor} = \frac{\text{Total waste (kg)}}{\text{kg product}}$$

Equation 4.3 The equation for the calculation of E-factor for a process or reaction.

Problems that can arise when using this metric include measuring the waste generated in a direct way, for this, the following equation can be used.

$$\text{E Factor} = (\text{mass of inputs} - \text{mass of outputs}) \div \text{mass of products}$$

Equation 4.4 Calculating E-factor when waste generation measurements are not possible.

The output of the system, in the simplest case, would include only the final desired products. In the case of recycling solvents or other reagents, these would also be included in the output, as they do not end up as waste. High E-factor scores signify more waste and as a consequence a greater negative impact on the environment, the goal for E-factor is always zero, this is also in agreement with one of the twelve green principles- waste should be prevented rather than treated. [13]

Defining what is waste can also pose a problem. When calculating E factor, water (apart from that formed during the process [85]) is often excluded from the calculation as this can lead to exceptionally high values. For example, in an aqueous waste stream, it is only the inorganic salts and organic compounds within the water that are included; the water itself is considered benign. High values caused by the inclusion of water can often cause difficulties when making meaningful comparisons between different processes. [81, 85]

Another problem is where the boundaries of the chemical process are drawn. When considering what to include as waste, there are some questions that must be clarified including: Is waste that is produced as a result of emissions treatment and energy use included? More information is needed.

Advantages of using E-factor include its ease of use and that it is very easy to understand. To begin with, all waste (excluding water) is measured, including washing solvents.

The E-factor as a metric is limited as it only considers the amount of waste and does not take into account the nature and environmental impact of the generated waste. To arrive at a more meaningful value the E-factor is multiplied by the environmentally hazardous quotient, Q, introduced by Sheldon. [78, 85] Q may have a value between 1 and 1000 based on the toxicity and ease of recycling of the chemical. For example, a value of 1 may be given to NaCl, which is relatively benign, whereas for a heavy metal, a value between 100-1000 may be assigned.[87] The environmental quotinent is also volume dependant, an example of this is the generation of sodium chloride. 100-1000 tonnes of sodium chloride per annum is unlikely to cause a waste problem and could be assigned a Q value of zero, however the generation of 10 000 tonnes per annum could potentially cause a disposal problem and hence be given a Q value above zero. [85]

Although this is could be a useful metric, it is still flawed as there is no common scale that can be used to assign a Q value to all forms of chemical reactions, therefore environmental quotient values are not transferable and cannot be compared unless the same values have been used for the same chemicals. Values are debatable and can vary from company to company and between different processes. However, in principle, the assessment of the environmental impact of the chemical is possible and is a useful tool when comparing alternative processes using the same values. [88]

Sheldon discussed in his review of the E-factor that he does not believe that there is an alternative metric that offers any advantage over the metric for showing how wasteful a process is. A comparison was made to the mass intensity metric where he notes that the ideal for this metric is 1 whereas the ideal for E-factor is 0, which he believes gives a better indication of the ultimate goal of producing zero waste. [85]

4.1.4 Effective Mass Yield (EMY)

Hudlicky *et al.* proposed a metric known as effective mass yield. [89] It is defined as 'the percentage of the mass of desired product relative to the mass of all non-benign materials used in its synthesis'. [70] It is expressed by the following and can also be estimated as 1/E, where E is defined as the E-factor.

$$\text{Effective mass yield (\%)} = \frac{\text{Mass of products} \times 100}{\text{Mass of non-benign reagents}}$$

Equation 4.5 The formula used to calculate effective mass yield

This metric was originally proposed as a way to overcome the production of significant amounts of benign waste (such as water) that ultimately meant that the values of E-factor calculated were higher and made it look like reactions and processes were having a greater negative impact on the environment than they actually were. [80] As already mentioned, a qualitative attempt at this was carried out by Sheldon with the introduction of the environmental quotient. [78]

This metric modifies the traditional concepts of synthetic yield by considering it in terms of the mass of the final product made from non-toxic materials. Although this is a useful metric, Lapkin states how it is prone to mis-use as there are no quantitative methods available to measure whether a reagent is benign or not and as a consequence it is difficult to establish what a totally benign material is as there is no agreed consensus. [83]

Hudlicky has attempted to define benign as 'those by-products, reagents or solvents that have no known environmental risk associated with them for example, water, low concentration saline, dilute ethanol, autoclaved cell mass, *etc*.' [89] However, as mentioned by Sheldon, [85] the impact of this waste is very volume dependant, which could pose a potential problem in the use of this metric. Therefore until toxicity information becomes routinely available for all chemicals it would be difficult to obtain a value of 'greenness' from this metric that could be used for accurate comparison of reactions and processes universally. However a rough estimate can be proposed following Hudlicky's definition of benign.

In a study of effective mass yield for several synthetic pathways, Hudlicky *et al*. proposed that neither atom economy nor chemical yields by themselves can provide an accurate picture of the overall processes with respect to the total waste component of the reaction. The benefits of effective mass yield are discussed by Hudlicky, explaining how it accounts for atom economy and the materials that do not contribute to the mass of by-products and hence giving a more accurate representation of desired mass expressed as a percentage of the total mass of the materials used during the synthesis of the product. [89] This is debatable due to the definitions of benign materials but it does give a good starting point.

4.1.5 Mass Intensity

Mass intensity takes into account the yield, stoichiometry, solvent and reagent used in the reaction mixture and expresses it as on a weight/weight basis, rather than a percentage. The goal for Mass intensity is as close to 1 as possible. [70]

$$\text{Mass intensity (MI)} = \frac{\text{Total mass used in a process or process step (kg)}}{\text{Mass of product (kg)}}$$

Equation 4.6 The equation used to calculate mass intensity

The Green Chemistry Institute Round Table has more recently used Process Mass Intensity (PMI) which is calculated in the same way as Mass Intensity, to benchmark the environmental impact and acceptability of processes used by its members. These were mainly leading pharmaceutical companies including those such as GlaxoSmithKline, Pfizer, AstraZeneca, Johnson & Johnson, and used as a driver to green the pharmaceutical industry. [85]

In the case of this metric, total mass used in a process includes all the chemicals used, reactants, catalysts, additives such as acids, bases, solvents etc. [90] Although this metric has been used a lot in the chemical industry, it fails to address all areas of a green reaction, however, it does draw attention to how wasteful the process is and Curzons *et al*. [73] have commented that they believe mass metrics are the best way to assess how green a process is.

4.1.6 Reaction mass efficiency (RME)

Reaction mass efficiency, developed by GlaxoSmithKline, is a measure of the percentage of the mass of the reactants that remain in the final product. The calculation includes the atom economy, yield and stoichiometry of the reactants. [73] It can be calculated in two ways:

For a generic reaction where A + B → C:

$$\text{Reaction mass efficiency} = \left(\frac{\text{m.w. of product C}}{\text{m.w. of A} + (\text{m.w. of B} \times \text{ molar ratio B/A}} \right) \times \text{ yield}$$

Or more simply:

$$\text{Reaction mass efficiency} = \left(\frac{\text{mass of product C}}{\text{mass of A} + \text{mass of B}} \right) \times 100$$

Equations 4.7 and 4.8 Alternative routes for the calculation of reaction mass efficiency

Reaction mass efficiency generally assesses the 'cleanness' of a reaction but fails to address the greenness of a whole process. It does not take into account waste produced. As with some of the other metrics already discussed, RME could show a reaction as being very green, but as waste has not been taken into consideration, there could be a chance that it isn't as green as first thought. With this in mind it would be helpful to use this metric in conjunction with others, for a more accurate assessment of how environmentally friendly the reaction is.

Andraos [71, 91] describes how recent reports have shown that reaction mass efficiency is a better and more useful metric than atom economy at measuring reaction performance. In a review of green chemistry metrics, Constable *et al*. comment how reaction mass efficiency is probably the most helpful metric for focusing chemists attention on how green their reactions and processes are, this is due to the fact that reaction mass efficiency accounts for all reactant mass and includes yield and atom economy.[70]

4.1.7 Carbon Efficiency

Carbon efficiency was developed and introduced by GlaxoSmithKline. This takes into consideration the yield, and the proportion of carbon in the starting materials that remains in the final product.

$$\%\ \text{Carbon efficiency} = \frac{\text{Amount of carbon in product} \times 100}{\text{Total carbon present in reactants}}$$

Equation 4.9 The equation used to calculate carbon efficiency

Although this is an interesting metric, in a study carried out by Constable *et al*. comparing several reactions, they discovered that carbon efficiency exhibits the same trends as reaction mass efficiency and does not offer any new insights into how to improve reaction conditions or chemistries. [70] However, this metric may be of particular interest to the pharmaceutical industry where carbon skeletons are key to their work.

4.1.8 The EcoScale

Van Aken *et al*. first introduced the EcoScale in 2006. The EcoScale is a semi-quantitative tool used to evaluate the quality of organic preparations based on yield, cost, safety, reaction conditions and ease of work up and purification. [87] This can be used as a powerful tool to assess and compare a number of reactions that ultimately lead to the same product, based on environmental and economical considerations- two of the said 'pillars of sustainability'. [4]

This metric works on a scoring system, scoring the reactions between 0-100, with 0 representing a completely failed reaction. Each parameter of the reaction is then analysed, for example, the toxicity of the chemicals involved, and the work up procedure. Within each parameter are individual penalty points assigned to the various situations that are taken into consideration when carrying out a chemical reaction.

Parameter	Penalty Points
6. Workup and Purification	
None	0
Cooling to room temperature	0
Adding solvent	0
Simple filtration	0
Removal of solvent with bp < 150 ˚C	0
Crystallisation and filtration	1
Removal of solvent bp > 150 ˚C	2
Solid phase extraction	2
Distillation	3
Sublimation	3
Liquid-liquid extraction	3
Classical chromatography	10

Table 4.2 An example of how the EcoScale assigns penalty points to unit operations involved in the reaction (only one section of the tool is shown).

Van Aken *et al*. discuss the differences between reactions at laboratory and industrial scale and how the relative weights of the parameters change depending on this. They discuss further by commenting that no restrictions on the use of reagents and solvents at laboratory scale exist, whereas in industry there would be restrictions in place for the use of extremely toxic or expensive one. [87] However, this point is debatable, especially when Green Chemistry and sustainability is considered and the introduction of legislation such as REACH. [23] Certain chemicals may be undesirable on a laboratory scale due to the need to replace them with alternatives for reasons such as toxicity to the users and the environment. Van Aken *et al*. also comment on how waste is a minor issue at laboratory but much more important at industry level due to the cost. [87] This point is valid in some contexts, however, in the case of the laboratories at the University of Bradford, waste management is one of the issues identified as being a problem in terms of being environmentally friendly.

Although this metric is useful in terms of comparing yield, cost, safety, reaction conditions and ease of work up and purification this metric does not consider important factors such as waste and resource usage (for example, electricity and water) so could not be used as the only method to assess how sustainable the reaction is. Another downside to this metric is that because it was designed for organic chemistry reactions, it could not be used in an undergraduate laboratory as a standard tool as it would not be applicable to all forms of chemistry, for example, experiments carried out in physical chemistry.

4.1.9 Summary of literature review

The following table summarises the advantages and disadvantages of the metric systems studied through this literature review:

Metric	Advantages	Disadvantages
Yield	- Gives a good indication of how well a reaction has performed - Relatively simple and easy to understand	- Does not take all areas of 'greenness' into account such as the production of by-products or energy intensive unit operations - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'.
Atom Economy	- Atom Economy can be calculated in planning stages which allows the most atom efficient route to a compound to be considered - Indicates how many atoms of the original reactants remain in the final product - Relatively simple and easy to understand	- Does not take all areas of 'greenness' into account such as toxicity of reagents or energy intensive unit operations - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'
E-Factor	- Draws attention to the amount of waste produced in a chemical process - Relatively simple and easy to understand	- Defining what waste is and the boundaries of the chemical reaction can pose a problem in determining what to include within the calculation. - Does not take all areas of 'greenness' into account such as toxicity unless the environmental quotient Q is applied; this contains flaws itself as there is not enough information available to apply this in an accurate way to allow comparison between reactions - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'.
Effective Mass Yield	- Using Hudlicky's definition of a benign material [89] this metric can give a rough estimate of how much product is formed from non-benign materials	- Prone to mis-use as there are no quantitative methods to measure whether a reagent is benign or not, until this information is available values are not comparable and obtaining an accurate value of 'greenness' is difficult - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'.
Mass Intensity	- Draws attention to how wasteful a process is by considering all weight in a process and expressing it on a weight/weight basis - Relatively simple and easy to understand	- Does not take all areas of 'greenness' into account such as toxicity of reagents or energy intensive unit operations - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'
Reaction Mass Efficiency	- Assesses the 'cleanness' of a reaction - Relatively simple and easy to understand	- Does not take all areas of 'greenness' into account such as toxicity of reagents or energy intensive unit operations - Cannot be used in isolation as it

		could give an inaccurate reading of 'greenness'
Carbon Efficiency	- Draws attention to how wasteful a process is in terms of how much carbon remains in the final product - Relatively simple and easy to understand	- Does not take all areas of 'greenness' into account such as toxicity of reagents or energy intensive unit operations - Cannot be used in isolation as it could give an inaccurate reading of 'greenness'
The EcoScale	- A useful tool for comparing a number of reactions - Considers many areas of a reaction including toxicity, work up and procedure	- Does not consider waste and resource usage - Weights of parameters - Not applicable to all processes, developed mainly for organic chemistry reactions

Table 4.3 Advantages and disadvantages of metric systems often applied to chemical processes to assess how green it is

In conclusion, the main message from this literature review is that although there are a range of useful metrics for assessing 'greenness' of reactions and processes, there is no single method that can be used for selecting the greenest route to a particular compound, or to simply assess the impact of the reaction on the environment. The EcoScale is useful in the organic chemistry laboratory and shows benefits for using it, however this still does not address all the necessary areas such as resource consumption.

A lack of information and general consensus on issues such as toxicity data is also hindering the successful use of metrics such as effective mass yield. Until information is available and uniform throughout various institutions and industry, these metrics cannot be used accurately unless they are limited to one specific area, however this would mean that a comparison of results throughout other institutions could not be possible unless the same toxicity information *etc* was adopted.

In terms of greening an undergraduate laboratory setting, it is obvious that just assessing a reaction using the traditional metric, reaction yield, does not bring attention to poor atom economy, reaction mass efficiencies or waste (resources, mass *etc*). A universal metric which addresses a number of issues within green chemistry to give one outcome is needed.

4.2 Experimental

A number of first and second year chemistry laboratory practicals have been tested using green chemistry metrics. This was carried out for two reasons:

1. To determine how effective these metrics are when applied to undergraduate practicals in terms of ease of use, applicability, understanding and reproducibility. This will also determine whether or not they could be used within a metric system addressing many areas of a process to identify how it performs in terms of being 'green'.
2. To determine the potential effect that the practicals have on the environment (for example in terms of waste production) and to identify any areas that could be improved in terms of green chemistry and sustainability, for example, water usage or complete experiment substitution

The metrics chosen to test were E-factor, atom economy, reaction mass efficiency, mass intensity, carbon efficiency and effective mass yield. They were chosen as they seemed most appropriate for an undergraduate laboratory due to the ease of calculation. The first three, e-factor, atom economy and reaction mass efficiency seemed good metrics to test due to their use and importance in industry.

The following practicals were tested (refer to appendix E for scripts):

- Purification of a liquid mixture by distillation and thin layer chromatographic (TLC) analysis
- Solvent extraction from a solid: Extraction and Purification of a Drug from a Tablet

- Solvent extraction from a liquid: Extraction and Purification of caffeine from tea
- Purification of solids by recrystallisation and sublimation
- Isolation and characterisation of a neutral organic compound from a mixture of inorganic and organic materials
- Extraction and characterisation of an acidic or basic organic solid compound from solution in a neutral organic liquid
- Preparation of Acetylsalicyclic acid (Aspirin)
- Reduction of a ketone to a secondary alcohol- cyclohexanone to cyclohexanol
- Preparation and analysis of polyiodides
- The Preparation of Tetraiodotin (IV) and its Triphenylphosphine Oxide Complex
- Determination of nickel in solution
- Determination of the rate constant in acid cat hydrolysis of an ester
- Effect of temperature on the rate of reaction, Determination of activation energy
- Polymer Science: Interfacial, Step Reaction Polymerisation; The Nylon Rope Trick
- Polymer Science: Stirred Interfacial Polymerisation

Each practical was carried out in exactly the same way that a student in the undergraduate laboratory environment would carry it out.

4.2.1 Results

Green chemistry metric results were calculated following the equations in the literature. The yields used in the calculations are based on recovery yields after purification, unless otherwise stated.

Table 4.4 Results of the application of green chemistry metrics to a selection of undergraduate practicals

	Metric							
Experiment	**Yield (g)**	**% Yield**	**E-factor**	**Atom Economy**	**EMY**	**Mass Intensity**	**RME**	**Carbon Efficiency**
Purification of a liquid mixture by distillation	36	90	0.03	N/A	N/A	1.11	N/A	N/A
Solvent extraction from a solid: Extraction and Purification of a Drug from a Tablet	0.40	82	0	N/A	N/A	78.65	N/A	N/A
Solvent extraction from a liquid: Extraction and Purification of caffeine from tea	0.22	76	439	N/A	N/A	1704	N/A	N/A
Purification of solids by recrystallisation and sublimation:								
Part A: Recrystallisation	1.54	78	0.18	N/A	Error	18.2	N/A	N/A
Part B: Sublimation	1.67	83	0.32	N/A	Error	1.2	N/A	N/A
Isolation and characterisation of a neutral organic compound from a mixture of inorganic and organic materials	1.92	92	33.53	N/A	2.68	54.8	N/A	N/A
Extraction and characterisation of an acidic or basic organic solid compound from solution in a neutral organic liquid								
Extraction of acidic organic solid	1.44	68	42.07	N/A	N/A	77.57	N/A	N/A
Distillation of organic liquid	16.04	93.8	0.058	N/A	N/A	1.07	N/A	N/A
Preparation of Acetylsalicyclic acid (Aspirin)	2.14	75	3.54	75	30.5	16.83	65	82

Reduction of a ketone to a secondary alcohol	4.63	49	4.55	102	5.42 3	56.9	45.8	100
Preparation and analysis of polyiodides:								
Preparation	2.14	94	12.3 5	100	22.6	13.6	93	100
Analysis	0.35	N/A	221	63.6	239. 6	N/A	N/A	N/A
The Preparation of Tetraiodotin (IV) and its Triphenylphosphine Oxide Complex:								
Preparation of Tetraiodotin (IV) from the elements	1.87	85	24.4 9	100	6.44	38.3	88	N/A
Preparation of Tetraiodotin (IV) from dichlorotin(II) dihydrate	2.29	82	14	90	23.9	21.4	44.2	N/A
Preparation of tetraiodobis(triphenylphosphineoxide) tin(IV)	1.45	77	7.69	102	9.56	10.46	76.3	100
Gravimetric and Compleximetric Analysis: Determination of nickel in solution:								
Gravimetric Analysis	0.25	N/A	778	88	0.32	390.8	0.47	100
Titration Analysis	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Polymer Science: Interfacial, Step Reaction Polymerisation; The Nylon Rope Trick	1.01	83	196. 7	63.76	1.53	805	30.4	100
Polymer Science: Stirred Interfacial Polymerisation	3.12	70	63.7	86	1.54	129.1	53	100
Electronic Effects of Axial Ligand Field Strength in Tetragonal Nickel (II) Complexes:								
Preparation of $[NiCl_2(Et_2en)_2].H_2O$	0.26	91	17.4	79	61.7	24.2	59.5	100
Preparation of $[Ni(NO_3)_2(Et_2en)_2]$	0.22	73	27.9	80	42.3	27.4	42	100
Preparation of $[Ni(NCS)_2(Et_2en)_2]$	0.27	92	20.3	51.4	39.7	22.9	39.7	100
Preparation of $[NiI_2(Et_2en)_2]$	0.29	67	24.2	61	35.4	35.5	35.4	100
Preparation of a Tetraaza Macrocycle (*Trans*-[14]-Diene) and its Coordination Chemistry with Nickel (II) and Copper (II)								
Preparation of 1,2-diaminoethane dihydrobromide	27.6	95	2.24	100	13.9	7.15	19.2	100
Preparation of trans-[14]-diene dihydrobromide dihydrate	6.98	72	12.6	85	12.7 8	7.82	99	100
Preparation of meso- and rac-trans-[14]-diene copper(II) bromide	0.25	50	69.2 7	86	0.00 8	113.28	25	100

Determination of the rate constant in acid cat hydrolysis of an ester	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Effect of temperature on the rate of reaction, Determination of activation energy	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
The Preparation of a Heterocyclic Compound Related to Nicotinamide	3.04	82	24.8	80.4	6.52	38.6	66	100

Table 4.4 Results of the application of green chemistry metrics to a selection of undergraduate practicals

4.2.2 Discussion

A number of undergraduate chemistry experiments have been carried out in order to apply green chemistry metrics. These metrics were applied to test the following:

1. To determine how effective these metrics are when applied to undergraduate practicals in terms of ease of use, applicability, understanding and reproducibility

2. To determine the potential effect that the practicals have on the environment and to identify any areas that could be improved in terms of green chemistry and sustainability, for example, water usage or complete experiment substitution

4.2.2.1 Discussion of findings for undergraduate experiments

Purification of a liquid mixture by distillation and thin layer chromatographic (TLC) analysis

This practical consists of two parts, a distillation of an unknown coloured solvent and thin later chromatography. The analytical part of this practical was not tested using metrics as the quantities were so small, and there was no synthesis or transformation due to this being an analytical technique.

The distillation produced a good recovery yield of 90%. The E-factor of 0.03 showed that this process did not have a large negative impact on the environment in terms of waste, as there was only 1.2 g of waste which consisted of the remaining fraction of the solvent used. The mass intensity (1.11) also showed that this process was not showing a large negative impact, as the result was extremely close to the target of 1. Atom economy, effective mass yield, reaction mass efficiency and carbon efficiency could not be calculated for this process as it did not include a synthesis.

Although this process showed a low negative impact in terms of use of resource and production of waste, the nature of a distillation process requires some form of cooling, in this case, water is used. With the water flowing at a slow and steady speed, the total water usage for this process was 9.5 L. If this was to be included in the calculation of E-factor, it would increase from 0.03 to 263.9, which shows just how much wastage has occurred.

Solvent extraction from a solid: Extraction and Purification of a Drug from a Tablet

This practical includes an extraction of paracetamol, ibuprofen or aspirin from a tablet using acetone as a solvent to extract the crude drug. The drug is then recrystallised using a small quantity of water.

0.40 g of the crude drug was extracted, the recrystallisation gave a good recovery yield of 82%, showing that the solvent usage (type and volume) was adequate to show the students a high yield. The E-factor for this practical was calculated as 0 as the water from the recrystallisation was excluded from the calculation. There was also no measurable extraction solvent, as this was evaporated to dryness on a water bath, so in theory there was more waste, however it was not measureable at the end of the process. The mass intensity for this extraction and recrystallisation showed a negative impact at 78.65 (aim for MI = 1) this was due to the large volume of solvent used to extract such a small quantity of target product.

Atom economy, effective mass yield, reaction mass efficiency and carbon efficiency could not be calculated for this process as it did not include any synthesis.

Solvent extraction from a liquid: Extraction and Purification of caffeine from tea

This practical includes the use of several solvents in the extraction and recrystallisation of caffeine from tea.

The crude caffeine extracted was 0.29 g and the recovery yield 0.22 g (76%). Although a reasonably good recovery yield was achieved, the E-factor, calculated excluding water, gave a result of 439, showing the production of a very high amount of waste. Including water, the E-factor would have been exceptionally high at 1561.6. The waste consisting of dichloromethane, acetone, petroleum ether and sodium sulphate came to a final weight of 96.76 g, which could seem like a small amount, however in comparison to the weight of target product, is very high. Also, in the context of an undergraduate laboratory, potentially there could be over thirty times this amount of waste generated due to the number of students carrying out the practical on their own. The dichloromethane waste also poses a problem as it is harmful and potentially carcinogenic. This waste must be managed correctly as it should not be released to the environment, which also means a cost for correct disposal.

The mass intensity of this practical was 1704, showing a high ratio of mass used in the extraction and recrystallisation to the mass of the final product. This mass was mostly related to the solvents used.

The atom economy, effective mass yield, reaction mass efficiency and carbon efficiency could not be calculated for this process as it did not include a synthesis.

Purification of solids by recrystallisation and sublimation

This practical includes the recrystallisation of impure benzoic acid or cinnamic acid contaminated with charcoal, and the sublimation of impure naphthalene. To avoid repetition only one of the recrystallisation of impure solids was carried out- benzoic acid.

The recrystallisation of benzoic acid showed a good recovery yield of 78%, however this could not be made reproducible as the quantities of charcoal mixed with the pure benzoic acid vary each time. Therefore low recovery yields may not always be a result of poor technique. The E-factor showed a low production of waste in relation to product with a result of 0.18. It was calculated excluding water and including the charcoal waste removed (0.29 g). This waste would not necessarily have a negative impact on the environment so this practical performs well in terms of waste. Including water used as the recrystallisation solvent, in the calculation gives an E-factor of 17.3 which in comparison to other E-factor results included in this section, is still reasonable. The nature of the waste does not pose any obvious problems as it is relatively benign.

The mass intensity for this recrystallisation was 18.2, as this was a purification, it was only the solvent that was contributing to the mass. Although this is higher than the target mass intensity of 1, it is still reasonable.

The sublimation of impure naphthalene showed a good recovery of 83%, as mentioned in relation to the recrystallisation of benzoic acid, as charcoal is added in various quantities to 'make the solid impure' a low recovery may not be the result of poor technique. The E-factor for the sublimation was 0.32 which shows a very low amount of waste in relation to product. The only waste resulting from the sublimation was the charcoal (0.54 g) extracted from the starting material. The mass intensity for the sublimation was 1.2 which is extremely close to the target of 1. The target could not be reached for this process as it was only a purification and some of the mass would not be incorporated into the final product as it was removed as an impurity. The mass intensity, along with the recovery is also an indication that the majority of naphthalene was purified.

Atom economy, reaction mass efficiency and carbon efficiency for both the recrystallisation and sublimation, could not be calculated due to the nature of this practical. It was noted that effective mass yield could not be calculated as the mass of non-benign reagents was zero, meaning that this metric could not be used as it is not mathematically feasible to divide by zero.

Isolation and characterisation of a neutral organic compound from a mixture of inorganic and organic materials

The isolation of a neutral organic compound from a mixture of inorganic and organic materials includes the use of the solvents water and dichloromethane, and the separation to extract the desired compound. This compound is then recrystallised from ethanol and water.

This isolation process showed a good recovery yield of 92%. The E-factor, calculated excluding water waste, showed the production of quite a large amount of waste in relation to desired compound with a score of 33.53, this was the result of acid and base washing- Hydrochloric acid and Sodium hydroxide, and the use of the solvents dichloromethane and ethanol during separation and recrystallisation. The nature of the remaining waste did not pose much of a problem as the volumes were relatively small and could be neutralised. The dichloromethane waste must be dealt with in the correct manner due to toxicity issues and so was the only solvent to raise concern. The mass intensity for this process was quite high at 54.8 and showed that a large mass of materials were needed to extract and purify a small amount of product. This mass was mostly consisting of solvents. The effective mass yield calculated as 2.68% showed that only 2.68% of the product was formed from non-benign materials.

Atom economy, effective mass yield, reaction mass efficiency and carbon efficiency were not applicable due to the nature of the practical and the lack of any synthesis stages.

Preparation of Acetylsalicyclic acid (Aspirin)

This practical involves the organic synthesis of acetylsalicylic acid from salicylic acid and acetic anhydride.

The crude yield of 88% and the recovery yield of 75% were relatively high for the synthesis of acetylsalicylic acid. The E-factor was calculated excluding water, which gave a result of 3.54, this showed that there was a very small amount of the waste produced in relation to target product. The waste produced was based on an estimate weight of sulphuric acid, acetic anhydride and salicylic acid residues. Including water waste in the calculation of E-factor gave 31.6, showing that the majority of the waste generated through this synthesis was water, which should not cause any problems associated with toxicity and disposal.

The atom economy of the synthesis of aspirin was based on salicylic acid and acetic anhydride, giving a result of 75%, meaning that three quarters of the original starting materials were incorporated into the final product, the target for atom economy is obviously 100%, therefore incorporating every atom into the new molecule. However, an atom economy of 75% was still reasonable.

The effective mass yield was calculated using the masses of salicylic acid, acetic anhydride and sulphuric acid which gave 30.5%, which refers to the amount of the product which is formed from non toxic reagents. A higher percentage would be more desirable in this instance.

The mass intensity of this synthesis was 16.83, which was high in relation to the target of 1. However the majority of this mass was due to the addition of water during the synthesis and the solvents used for recrystallisation. The reaction mass efficiency of 65% showed that over half of the mass of the reagents used within the synthesis were incorporated into the final product. 82% of the carbon within the starting materials remained in the final product, showing a good carbon efficiency for this reaction.

Reduction of a ketone to a secondary alcohol

The reduction of a ketone to a secondary alcohol involves the transformation of cyclohexanone to cyclohexanol using sodium borohydride as a reducing agent.

The yield of cyclohexanol was fair, 49%. The E-factor calculated (excluding water) for this transformation was 4.55, showing that it did not produce large amounts of waste in relation to product. The atom economy for this reaction was 102% as the ketone must gain a hydrogen atom in order to be reduced to a secondary alcohol.

The effective mass yield, calculated using the masses of the non-benign reagents cyclohexanone, methanol, sodium borohydride, sodium methoxide, hydrochloric acid and diethyl ether. This gave a score of 5.4%, which corresponds to the amount of product prepared from non-toxic materials. The mass intensity for the reduction of cyclohexanone to cyclohexanol was quite high, 56.9, as a result of the large amounts of solvent use- methanol and diethyl ether. The reaction mass efficiency was 45.8% showing that less than half of the mass of the original reagents was incorporated into the final product. This reaction gave a high carbon efficiency of 100%, indicating that the carbon used in the starting materials remained in the final product.

Polymer Science: Interfacial, Step Reaction Polymerisation; The Nylon Rope Trick

This practical involves the polymerisation of nylon from 1,2-dichloroethane and hexamethylene diamine.

A high yield of 83% was obtained for the production of nylon. The E-factor, calculated excluding water, gave a value of 196.7 which showed that there was quite a significant amount of waste produced in relation to the product. This waste mainly consisted of the hydrochloric acid used to feed the polymer into and acetone used to rinse the polymer after the reaction was complete. Calculating the E-factor including water gave a score of 684.2, showing the significant amounts of water (500 cm^3) that this practical requires to wash the polymer after the reaction. On its own this reaction may not have such a huge effect in terms of water use, however in an undergraduate laboratory with potentially over thirty students carrying out this reaction the water usage would build up. However, although large volumes of water are required, if a washing solvent is needed, water would have the least negative impact on the environment, as opposed to using acetone for the whole washing process.

The atom economy for the polymerisation was calculated using the repeating unit and gave a result of 63.76% atom efficiency, this has taken into account the loss of HCl during the formation of peptide linkages as part of the polymerisation process. However, the reaction, assuming 100% conversion, is very atom economic.

The mass intensity score of this practical was extremely high at 805. The majority of the mass was due to the volume of water, acetone and hydrochloric acid used. The reaction mass efficiency was extremely low at 30.4% which showed that the mass used within the reaction was not incorporated into the final product. The carbon efficiency for this process was 100% showing that the carbon in the starting products remained in the final product. The effective mass yield of 1.53% showed that only this percentage of the product was formed from non-toxic reagents.

This practical did not use any electricity in the form of heating *etc* therefore positively impacting on the environment.

Polymer Science: Stirred Interfacial Polymerisation

This practical involves an interfacial polymerisation reaction between phenolphthalein and terephthaloyl chloride, using stirring.

The yield of 3.12 g (70%) obtained was good; however it could have potentially been improved. The E-factor for this reaction was calculated excluding water and gave a score of 63.7, indicating that quite a large amount of waste was produced in relation to the product. This waste mainly consisted of acetone and 1,2-dichloroethane. (~199 g) Including water in the E-factor calculation, gave a value of 117.5, showing that water is contributing an amount to the waste.

The atom economy calculated based on one repeating unit was 86%, showing a high number of atoms were incorporated into the final product. This atom economy is lower due to the fact that HCl is lost during the polymerisation process to allow for the formation of peptide linkages to form the polymer, therefore this reaction could never be 100% atom efficient.

The effective mass yield of this practical was 1.54% showing the percentage of the product formed from benign reagents. The carbon efficiency was 100% as the carbon in the starting products remained in the final product, this is also based on 100% conversion. The mass intensity of this experiment was extremely high at 129.1 in relation to the target of 1. This was mostly due to the use of water and solvents such as acetone and 1,2-dichloroethane. The reaction mass efficiency of this practical was 53%, this could have been due to the yield, an increase in the yield would mean that more of the mass of the reactants had been incorporated into the mass of the final product, giving a higher score.

Preparation of a Tetraaza Macrocycle (*Trans*-[14]-Diene) and its Coordination Chemistry with Nickel (II) and Copper (II)

This practical involves the synthesis of trans-[14]-diene dihydrobromide and the preparation and characterisation of its nickel (II) and copper (II) complexes. To avoid repetition of the procedure, only the nickel (II) complexes were formed.

Part A: Preparation of 1,2-diaminoethane dihydrobromide

The preparation of 1,2-diaminoethane dihydrobromide yielded 27.6 g (95%). It was noted that this was an exceptionally high yield and could potentially be scaled down by at least four as the rest of the experiment only required 5.55 g of the product for the preparation of the macrocycle molecules. Either this or the product could be shared out amongst a group of students.

The E-factor for this synthesis was 2.24, which showed that there was not a huge amount of waste produced in relation to the product. The waste consisted mainly of methanol used as a solvent and diethyl ether used to wash the final product. This reaction boasted a high atom economy of 100%, this was due to the nature of the synthesis and the fact that it is an addition reaction.

The effective mass yield was calculated as 13.9%, showing that only 13.9% was formed from non-toxic materials. The mass intensity of this synthesis was reasonable at 7.15, although there was a high mass involved; the high yield balanced this out somewhat. The reaction mass efficiency of the reaction gave a result of 19.2% which was a low score for this area.

The carbon efficiency of the synthesis was 100%, showing that the carbon in the starting materials remained in the target product.

This part of the practical does not require any additional power or resources such as water.

Part B: Preparation of trans-[14]-diene dihydrobromide dihydrate

This reaction produces the macrocyle trans-[14]-diene dihydrobromide dihydrate, formed from 1,2-diamino dihydrobromide, 1,2-diaminoethane and acetone.

6.98 g (72%) of trans-[14]-diene dihydrobromide dihydrate was obtained in this practical. The amount of product was sufficient for the next parts of the experiment and did not show an over production that could lead to waste. The E-Factor of this part of the procedure was 12.6, which meant that a reasonable amount of waste was generated as well as the production of the desired compound. The waste generated was mainly solvent- acetone and diethyl ether.

The mass intensity was measured at 7.82, which was not an exceptionally bad score but showed the use of more mass not incorporated into the final product, this again was due to solvents. The reaction mass efficiency was 99%, scoring very high and showing that that the majority of the mass of the reactants formed the final product. The atom economy was calculated at 85% showing that the majority of the atoms in the original reactants were used to form the final product. The effective mass yield showed that the final product was formed from 12.78% non toxic materials, this was poor in terms of green chemistry and sustainability. The carbon efficiency was 100% showing that all the carbon in the original reactants was present in the final product.

This preparation included refluxing the reagents for 45 minutes, this resulted in the use of 13 L of water flowing at a slow and steady rate to cool the reflux condenser.

Part C: Preparation of meso- and rac-trans-[14]-diene copper(II) bromide

The preparation of meso- and rac-trans-[14]-diene copper (II) bromide gave a yield of 0.25 g (50%). This was a fair yield however longer reflux *etc* could have increased the yield. The E-factor of this part of the experiment was 69.27, showing a high amount of waste produced in relation to the product. This waste was mostly due to methanol and diethyl ether.

The atom economy for this reaction was calculated as 86%, which indicates that a large number of the molecules in the starting materials were incorporated into the final product, showing that this reaction is relatively green in terms of atom economy. The effective mass yield showed that 0.008% of the final product was produced from non-toxic reagents, which is far from the desired target of 100%. The mass intensity was 113.28, indicating that much more mass was used than that that formed the final product, the target for mass intensity is 1, the increase was mainly due to the solvents methanol and diethyl ether. The reaction mass efficiency was relatively poor in terms of green chemistry with a score of 25%, this meant that only 25% of the original mass of the reactants was incorporated into the final product. The carbon efficiency was classed as green due to its score of 100%.

Electronic Effects of Axial Ligand Field Strength in Tetragonal Nickel (II) Complexes

This practical includes the preparation of four tetragonal nickel (II) complexes with a variety of ligands. This allows students to compare the axial ligand strength within these complexes. The practical is performed on a 1 mmol scale, which is in favour of sustainable practise due to the requirement of less resource such as the reagents, production of less waste and shows cost benefits as less materials need to be purchased. The nickel salts used in this practical are potential carcinogen, however the risk of this is reduced significantly by the 1 mmol scale to carry out the practical.

Part A: Preparation of [$NiCl_2(Et_2en)_2$].$2H_2O$

[$NiCl_2(Et_2en)_2$].$2H_2O$ was prepared using $NiCl_2.6H_2O$ and Et_2en.

[$NiCl_2(Et_2en)_2$].$2H_2O$ was obtained with a 91% yield. The E-factor for this part of the practical was 17.4 which suggests a high amount of waste in relation to product. Although the E-factor was high, the actual waste only came to 4.86 g, consisting mainly of ethanol. According to Hudlicky, ethanol can be regarded as being benign, and as the volume was so small, this would be regarded as being a relatively green process in terms of waste, however, as the ethanol has been in contact with nickel salts, there is the chance of nickel residues remaining and for this reason, should not be disposed of down the sink.

The atom economy of the preparation of [$NiCl_2(Et_2en)_2$].$2H_2O$ was 79%, which was relatively good, showing that more than two thirds of the original reactants were incorporated into the final product. The atom economy for this practical could never be 100% as it is not an addition reaction, but rather a substitution reaction. The effective mass yield of this preparation was calculated excluding ethanol, and gave a result of 61.7%. This showed the percentage of the mass of desired product in relation to the mass of all non-benign materials used in its preparation.

The mass intensity for this preparation was 24.2, which was much higher than the target of 1. The mass was mainly due to the solvents that were not meant to be incorporated into the final product. The reaction mass efficiency calculation was in agreement with this showing that only 59.5% of the mass of the original reactants was incorporated into complex. This indicates that it was mainly the mass of the ligands that contributed to the loss in mass, but due to the nature of this practical, there would be some loss in mass incorporated into the final product anyway. The carbon efficiency for this preparation was 100% showing all carbon in the reactants was incorporated into the final product.

Part B: Preparation of [$Ni(NO_3)_2(Et_2en)_2$]

[$Ni(NO_3)_2(Et_2en)_2$] was prepared using $Ni(NO_3)_2.6H_2O$ and Et_2en.

The preparation of [$Ni(NO_3)_2(Et_2en)_2$] gave a yield of 73%. The E-factor of this preparation was 27.9 which indicated a high production of waste in relation to desired product. This waste was relatively small when compared to the waste generated in other practicals and came to 6.15 g, consisting mostly of ethanol. The atom economy for this preparation was 80% and showed that the majority of the reactants were incorporated into the final product. As already mentioned in relation to Part A, the atom economy could never reach 100% due to the nature of the practical.

The effective mass yield of [$Ni(NO_3)_2(Et_2en)_2$] was calculated as 42.3%, excluding ethanol. This gave an indication of the mass of the desired product in relation to the mass of all non-benign materials used in its synthesis. The mass intensity was 27.4, showing that a moderate mass of materials was used in relation to the mass of desired product, and was much higher than the target of 1. The extra mass was the result of solvents. The reaction mass efficiency backed this up, with a result of 42%, showing that only this amount of the original reactants were incorporated into the final mass of the product. However, this was again due to the nature of this practical and the chemistry occurring. The carbon efficiency was 100%, indicating all carbon in the reactants was present in the final product.

Part C: Preparation of $[Ni(NCS)_2(Et_2en)_2]$

$[Ni(NCS)_2(Et_2en)_2]$ was prepared using $Ni(NO_3)_2.6H_2O$, NaNCS and Et_2en.

$[Ni(NCS)_2(Et_2en)_2]$ was obtained with a high yield of 92%. The E-factor of this preparation was 20.3 which showed a moderate amount of waste had been produced in relation to the desired product. This waste mainly consisted of ethanol and weighed 5.48 g. The atom economy of $[Ni(NCS)_2(Et_2en)_2]$ was lower than the other complexes prepared in this practical, giving a result of 51.4%. This was mainly due to the nature of the chemistry occurring in this preparation and the substitution of ligands.

The effective mass yield of this part of the practical was 39.7% which gave an indication of the mass of desired product in relation to the mass of non-benign materials used in its synthesis. The mass intensity was 22.9 which showed that there was a moderate mass of materials used in relation to the production of the desired complex, this extra mass was mainly the result of solvents. The reaction mass efficiency was 39.7% which was quite low, showing that less than half of the original mass of the reactants remained in the final product. The carbon efficiency was high with a value of 100% showing that all the carbon in the reactants was present in the final product.

Part D: Preparation of $[NiI_2(Et_2en)_2]$

$[NiI_2(Et_2en)_2]$ was prepared using $Ni(NO_3)_2.6H_2O$, NaI and Et_2en.

$[NiI_2(Et_2en)_2]$ was obtained with a relatively high yield of 67%. The E-factor was 24.2, indicating that there was a moderate amount of waste generated in relation to desired product. However when considering the waste alone, it came to a total of 7.02 g, consisting mainly of ethanol, which was a very small amount in relation to other practicals. The atom economy of this process was quite low at 61%, this, as already mentioned is due to the nature of the chemistry involved in the preparation and could never reach 100%.

The effective mass yield was calculated to be 35.4% and excluded ethanol as it is considered by Hudlicky to be benign. This showed the percentage of the mass of desired product in relation to the mass of all non-benign materials used in its synthesis. The mass intensity was 35.5 which showed that quite a moderate amount of materials were used in the preparation which were not incorporated into the final product. This was mainly solvents. The reaction mass efficiency showed that only 35.4% of the original mass of the reactants was incorporated into the final product. The carbon efficiency of this preparation was high at 100%.

The Preparation of Tetraiodotin (IV) and its Triphenylphosphine Oxide Complex

This practical involves the preparation of a sample of tetraiodotin(IV) (stannic iodide) and the formation of its coordination complex with triphenylphosphine oxide. The iodide itself is prepared by two alternative methods which are carried out in pairs.

Part A: Preparation of Tetraiodotin (IV)

Method A: Preparation from the elements

Tetraiodotin (IV) was prepared from iodine and sheet tin in acetic acid and acetic anhydride and refluxed until the metal had been consumed.

A crude yield of 2.2 g of SnI_4 was obtained (72%), and 1.87 g (85%) after purification. The E-factor for the entire process was 24.49, showing that a moderate amount of waste was produced in relation to the amount of product. The benefit of using this method was that it exhibited a 100% atom economy due to the preparation of the compound directly from the elements, resulting in no production of by-products. Acetic anhydride and iodine were used in the calculation of effective mass yield which came to 6.44%.

The mass intensity of this process was 38.3 which showed the use of a moderate mass of materials not incorporated into the final product. Acetic acid and acetic anhydride mainly contributed to this mass. The reaction mass efficiency calculated from the crude yield was quite high at 88%, to increase the reaction mass efficiency, the reaction may have not quite gone to completion as the mass of the reactants had not been fully integrated into the final product, so should be left to reflux longer. As this compound does not include carbon, the carbon efficiency could not be calculated.

Part of this preparation included refluxing the reagents for approximately 45 minutes. The reflux condenser required the use of water to allow it to cool and condense the contents of the reflux vessel, with the water flowing at a slow and steady rate, 34.3 L of water was used, which was then disposed of down the drain.

Method B: Preparation from dichlorotin(II) dihydrate

Tetraiodotin (IV) was prepared from dichlorotin(II) dihydrate (stannous chloride dihydrate), which was refluxed in acetic acid and acetic anhydride to afford the dehydrated stannous chloride, this was then refluxed further in the presence of iodine.

Tetraiodotin(IV) was obtained with a low crude yield of 2.79 g (34%) and a recovery yield after purification of 2.29 g (82%). The E-factor, calculated using the recovery yield, was 14 which showed a relatively low production of waste in relation to product. The atom economy of this reaction was 90% due to the nature of the chemistry and the loss of two chlorine atoms, replaced by iodine. 90% showed a high atom efficient reaction.

The effective mass yield was calculated using the masses of acetic anhydride, stannous chloride dehydrate and iodine used in the reaction. The acetic acid was not included in this calculation according to Hudlickys definition to a benign material. The effective mass yield for this reaction was 23.9%.

The mass intensity of the preparation of tetraiodotin(IV) was 21.4, showing the use of materials not incorporated into the final product. This mass was mostly due to the use of acetic anhydride and acetic acid. The reaction mass efficiency was 44.2% showing that not all of the mass of the reactants had been incorporated into the final product, this was mostly due to the nature of this practical and the production of by-products. The carbon efficiency of this part of the practical could not be calculated as the reactants and products did not contain carbon atoms.

The reagents were left to reflux for approximately 35 minutes, in this time 35.5 L of water were used to cool the reflux condenser. This water was wasted, as it was not recycled and went down the drain.

Part B: Preparation of Tetraiodobis(triphenylphosphineoxide)tin(IV)

Tetraiodobis(triphenylphosphineoxide)tin(IV) was obtained with a good yield of 1.45 g, (77%). The E-factor of this part of the practical was 7.69, which indicated a slight production of waste in relation to product. This waste mainly consisted of dichloromethane, weighing only 11.1 g, which did not pose any particular problems with disposal.

The atom economy calculated for the preparation was 102%, the extra two percent was due to the oxygen present in the air contributing two oxygen atoms. This increase in atom economy is high as the original reagents do not contain this oxygen and it was not included, if it was the atom economy would be 100%, showing an excellent atom efficient process. The effective mass yield of this process was 9.56%.

The mass intensity at 10.46 indicated materials used that weren't incorporated into the final product, this was the result of using dichloromethane as a solvent to allow the reagents to react. The reaction mass efficiency, 76.3%, showed that the reaction had not used all the mass of the reactants in the final product, leaving the reaction to proceed longer could have perhaps increased this value. The carbon efficiency of this process was 100% as the carbon in the triphenylphosphine starting material remained in the final product.

Preparation and analysis of polyiodides

This practical involves the preparation of the polyiodides I_3^- and I_5^- utilising the tetramethylammonium cation as a counterion that stabilises the polyiodide species in the solid state. The products are then analysed for their iodine content using a gravimetric procedure based on precipitation of AgI from a solution of product with aqueous silver nitrate. In the case of applying metrics, only the I_3^- polyiodides were prepared.

Part A: Preparation of tetramethylammonium triiodide

The polyiodide I_3^- was formed from iodine and tetramethylammonium iodide, and heated on a water bath to allow the reaction to proceed.

The polyiodide I_3^- was obtained with a high yield of 2.14 g (94%). The E-factor was calculated at 12.35 which indicated the production of a moderate amount of waste in comparison to the final product. The waste consisted mainly of ethanol and some diethyl ether and came to a total of 26.43 g. The atom economy of this process was 100% indicating all of the atoms in the reactants are incorporated into the final product, obviously depending on 100% conversion. This also means that there is no further production of by-products.

The effective mass yield was 22.6%. The mass intensity of 13.6 indicated that there was more mass used than target complex produced, however this was not too high in comparison to other practicals. The extra mass was the result of solvents. The reaction mass efficiency was high at 93%, showing that the majority of the mass of the reactants was used to form the final product. The carbon efficiency was high at 100%, showing all carbon in the starting materials was incorporated into the target complex.

Part B: Analysis of polyiodides

Part B of this practical includes allowing the students to perform elemental analysis by determining the percentage by weight of iodine present in the compound. Aqueous silver nitrate is used to form a precipitate of silver iodide which can then be dried to a constant weight, weighed and the iodine content calculated from this.

The yield of silver iodide was 0.35 g. The E-factor calculated for this reaction, excluding water, was 221 this shows that a high amount of waste was produced in relation to product. The atom economy was calculated at 37.6% which was poor in terms of green chemistry, however due to the nature of the chemistry being carried out in order to perform elemental analysis; it would not be possible to achieve a 100% atom economy.

The effective mass yield of the reaction was calculated as 63.6%, indicating that 63.6% of the compound was formed using non-toxic materials. The mass intensity was much higher than the target of 1, at 239.6 showing that a high amount of reagents and solvents were used in order to form the product, this was mainly due to the use of silver nitrate solution.

Reaction mass efficiency was not calculated as it was thought that it was not applicable to this type of reaction. Carbon efficiency could not be calculated due to the lack of carbon within the compounds.

Extraction and characterisation of an acidic or basic organic solid compound from solution in a neutral organic liquid

This practical allows students to use a range of techniques such as separation, distillation and recrystallisation. Each student is given a sample of liquid containing either an acidic or a basic compound, they must use the techniques that they have been taught in previous laboratory sessions to extract the compound. The neutral organic liquid which the organic solid is extracted from is purified by distillation.

Part A: Extraction of acidic organic compound

The yield of the unknown acidic compound was 1.44 g (68%) after purification by recrystallisation. The E-factor was 42.07 showing a moderate amount of waste (60.58 g) was produced in relation to product. This waste mainly consisted of dichloromethane, hydrochloric acid and sodium hydroxide. The mass intensity of the extraction and recrystallisation was 77.57, indicating a high amount of materials used in relation to the product obtained, this mass was mainly solvents, hydrochloric acid and sodium hydroxide.

Atom economy, effective mass yield, reaction mass efficiency and carbon efficiency could not be calculated due to the nature of the practical.

As the students are not aware of which compound they have until they have evaporated off the solvent, they must repeat the extraction twice, in each case, one of the extractions will not yield a product. The unknown liquid used contained an acidic organic compound, and as a result a basic organic compound was not yielded. Metrics could not be applied to this part of the practical as there was no mass of product, which is needed in the majority of calculations. The resultant waste from this was 65.53 g consisting mainly of dichloromethane and small amounts of hydrochloric acid and sodium hydroxide.

Part B: Purification of neutral organic liquid by distillation

The organic liquid was distilled from 17.1 g impure liquid and gave a recovery yield of 16.04 g (93.8%). The E-factor of this distillation was 0.058 showing a very low production of waste during this process, the waste came to 0.94 g and consisted of the remaining liquid and impurities. The mass intensity of 1.07 showed that the majority of the materials were present in the final product, which would be expected for this type of process. As this is purification, the waste and mass intensity could never be ideal due to the removal of impurities. Atom economy, effective mass yield, reaction mass efficiency and carbon efficiency could not be calculated due to the nature of the process and the unknown materials and quantities.

The distillation used 12.5 L of water.

Gravimetric and Compleximetric Analysis: Determination of nickel in solution

In this practical, students use two techniques to determine the amount of nickel in an unknown solution.

Part A: Gravimetric determination of nickel using dimethylglyoxime

The gravimetric determination of nickel in solution includes using an alcoholic solution of dimethylglyoxime to complex with and precipitate out the nickel. This precipitate is then dried to a constant weight which then allows the students to derive an estimate of the amount of nickel in the original solution.

The yield of $Ni(DMG)_2$ was 0.25 g. The E-factor for this part of the practical was 778, indicating a high production of waste in relation to product. The E-factor was calculated excluding the water washings. The waste consisted mainly of residues of ammonium hydroxide solution and HDMG, and water generated through the complexation of the $[OH^-]$ ions from the ammonium hydroxide and the $[H^+]$ lost by HDMG when complexing with another HDMG molecule and nickel. Usually water would not be included in this calculation, however, the quantity generated was not known. The reaction mass efficiency calculated was 0.47%, showing that only 0.47% of the mass of the original reactants was incorporated into the final product, this was due to the nature of the chemistry to precipitate out the product

The atom economy of this reaction was 88%, which indicates a high percentage of the original reagents were incorporated into the desired product. This reaction could never reach 100% percent as it includes the complexing of two HDMG molecules which results in the loss of two protons. The water balancing the Ni(II) is also not used in the formation of the final product.

The mass intensity of this process was very high at 390.8, in comparison to the target of 1. This was due to the use of ammonium hydroxide and dimethylglyoxime this is reflected in the reaction mass efficiency which was calculated as 0.46%. The carbon efficiency of this process was 100% as all the carbon in the HDMG was used in the complex of $Ni(DMG)_2$. The effective mass yield of this experiment was calculated as

0.32% showing a poor score in terms of green chemistry and an indication that 0.32% of the product was formed from non-toxic reagents.

Part B: Complexometric titration of nickel using EDTA

The unknown nickel solution was titrated against standard EDTA solution in order to determine the amount of nickel in the original solution.

Green chemistry metrics could not be applied to this part of the experiment due to the nature of titration methods and the lack of a production of a measureable product. The titration was repeated three times and until the difference between titres of successive runs was 0.05 cm^3. The total waste for the titrations was 386.66 g. The disposal of this waste poses a problem in terms of cost and safe disposal, as nickel solutions can be considered as dangerous for the environment. The concentration of nickel in this waste is relatively low, but could have effects on the environment if a class of 30 students were to dispose of this amount of waste down the drain.

The Preparation of a Heterocyclic Compound Related to Nicotinamide

The synthesis of 3-cyano-4,6-dimethylpyridin-2-one is carried out from the reaction of cyanoacetamide and pentan-2,4-dione.

3-cyano-4,6-dimethylpyridin-2-one was obtained in a good yield of 3.04 g (82%). The E-factor of this synthesis was 24.8, and was calculated excluding water. The waste was mainly due to ethanol and sodium carbonate. The atom economy of this reaction was 80.4% indicating that there was a small production of by-product, however the majority of the original atoms were incorporated into the final product.

The effective mass yield of this synthesis was 6.52%. The mass intensity of this process was 38.6, showing that there was much more mass used than what was incorporated into the final product. However, this is the result of solvents. The reaction mass efficiency showed that 66% of the original mass of the reactants were incorporated into the final product, approximately 34% of this mass was either un-reacted starting materials, the yield points to the reaction not going to full completion, therefore this could be a possibility or mass forming by-products. The carbon efficiency was high at 100%, indicating that all the carbon in the original reactants was incorporated into the final product.

4.2.3 Summary of findings

4.2.3.1 Waste

From the results of the undergraduate practicals tested, it is obvious that the majority of waste generated in the laboratory, during the experiment alone is solvent waste. There is also a high usage of water within these practicals which again ultimately ends up as waste as there is no system in place to avoid the use of water during distillation and reflux. Measures such as a recycling system for the water could be put into place, or more simply, the use of so called dry cooling, in the form of air condensers which do not require the use of water.

A joint project with the University of York discovered that solvent usage is often excessive in an undergraduate setting. An undergraduate experiment involving an adulterated pharmaceutical (AP) consisting of a mixture of aspirin and acetanilide was carried out and aimed to investigate the minimal amount of solvent required to dissolve the mixture. This was carried out in parallel to the usual procedure in order to compare yields. The results of the study showed that twice as much solvent as is necessary to dissolve the AP was used in the original procedure and by reducing the solvent usage the yield was not affected. If this could be applied to undergraduate practicals at the University of Bradford, it could mean that waste could be reduced, giving environmental and cost benefits.

4.2.3.2 Scale

It has been noted that some reactions could be scaled down, due to the over production of desired compound. An example of this is in the preparation of 1,2-diaminoethane dihydrobromide where 27.6 g of the compound was yielded. The other steps of the practical only required 5.55 g of this, which meant that the remaining 22.05 g was wasted. With practicals such as the synthesis of acetylsalicylic acid where no further transformations are carried out it would be possible to perhaps scale the reaction down and still have enough sample to carry out a melting point determination. This would also give students more experience of working at smaller scales which is often typical in the chemical industry.

Mayo *et al*. comment that nearly everything in the laboratory ends up as waste and once the desired compounds are produced, characterised and tested, they may be stored for a while but ultimately they are discarded. [92] With this in mind, it would be more beneficial for reactions to be scaled down, to reduce waste and resource usage, and also costs.

4.2.3.3 Applicability

It is evident that the metrics present in the literature are not applicable to all forms of chemistry practical. When testing the metrics, it became apparent that only organic synthesis practicals would allow the application of all of them.

The application of green chemistry metrics also requires a measurable product, therefore in the case of physical chemistry practicals such as ‘Determination of the rate constant in acid catalysed hydrolysis of an ester’ and inorganic chemistry practicals involving titrations, it is not possible to apply a single metric. This means that students would not be able to assess the impact of their experiments based on these green chemistry metrics.

In order to apply metrics such as atom economy and reaction mass efficiency, the original reagents or reactants must be known, therefore for practicals such as the solvent extraction from a solid or liquid, it is not possible to apply them. This is also due to the nature of the chemistry being performed, as the metrics described in the literature are more suitable to synthesis. Effective mass yield is not applicable in the case of those reactions involving no usage of non-benign materials, the equation for calculating the EMY is as such that it would require dividing by zero, which is not mathematically possible.

	Metric						
Experiment	**Yield**	**E-factor**	**Atom Economy**	**EMY**	**Mass Intensity**	**RME**	**Carbon Efficiency**
Purification of a liquid mixture by distillation	✓	✓	✗	✗	✓	✗	✗
Solvent extraction from a solid: Extraction and Purification of a Drug from a Tablet	✓	✓	✗	✗	✓	✗	✗
Solvent extraction from a liquid: Extraction and Purification of caffeine from tea	✓	✓	✗	✗	✓	✗	✗
Purification of solids by recrystallisation and sublimation	✓	✓	✗	✗	✓	✗	✗
Isolation and characterisation of a neutral organic compound from a mixture of inorganic and organic materials	✓	✓	✗	✗	✓	✗	✗
Extraction and characterisation of an acidic or basic organic solid compound from solution in a neutral organic liquid	✓	✓	✗	✗	✓	✗	✗
Preparation of Acetylsalicylic acid (Aspirin)	✓	✓	✓	✓	✓	✓	✓
Reduction of a ketone to a secondary alcohol	✓	✓	✓	✓	✗	✓	✓
Preparation and analysis of polyiodides:							
Preparation	✓	✓	✓	✓	✓	✓	✓
Analysis	✓	✓	✓	✓	✓	✗	✗

The Preparation of Tetraiodotin (IV) and its Triphenylphosphine Oxide Complex:							
Preparation of Tetraiodotin (IV)	✓	✓	✓	✓	✓	✓	✗
Preparation of tetraiodobis(triphenylphosphineoxide) tin(IV)	✓	✓	✓	✓	✓	✓	✓
Gravimetric and Compleximetric Analysis: Determination of nickel in solution:							
Gravimetric	✓	✓	✓	✓	✓	✓	✓
Titration	✗	✗	✗	✗	✗	✗	✗
Polymer Science: Interfacial, Step Reaction Polymerisation; The Nylon Rope Trick	✓	✓	✓	✓	✓	✓	✓
Polymer Science: Stirred Interfacial Polymerisation	✓	✓	✓	✓	✓	✓	✓
Electronic Effects of Axial Ligand Field Strength in Tetragonal Nickel (II) Complexes	✓	✓	✓	✓	✓	✓	✓
Preparation of a Tetraaza Macrocycle (*Trans*-[14]-Diene) and its Coordination Chemistry with Nickel (II) and Copper (II)							
Preparation of 1,2-diaminoethane dihydrobromide	✓	✓	✓	✓	✓	✓	✓
Preparation of trans-[14]-diene dihydrobromide dihydrate	✓	✓	✓	✓	✓	✓	✓
Preparation of meso- and rac-trans-[14]-diene copper(II) bromide	✓	✓	✓	✓	✓	✓	✓
Determination of the rate constant in acid cat hydrolysis of an ester	✗	✗	✗	✗	✗	✗	✗
Effect of temperature on the rate of reaction, Determination of activation energy	✗	✗	✗	✗	✗	✗	✗
The Preparation of a Heterocyclic Compound Related to Nicotinamide	✓	✓	✓	✓	✓	✓	✓

Table 4.5 The applicability of green chemistry metrics to a selection of undergraduate practicals

4.2.3.4 Ease of applying within an undergraduate laboratory environment

To use green chemistry metrics in an undergraduate laboratory setting it is extremely important that they are easy to apply. Atom Economy and carbon efficiency are easy to apply provided that the student has a balanced equation for the reaction that they are carrying out. This can also be calculated before the session as the desired product weights are not required, therefore this would not impact the practical session at all in terms of time.

To calculate the E-factor, the weight of the waste generated throughout the practical is required. In an undergraduate practical session, time scales can often be tight; therefore it could be impractical for each student to weigh out their waste. On the other hand, if the students can visualise how much waste is being generated it could raise their awareness of the impact that they are potentially making on the environment. With this in mind it may be more practical for each bench of students to collect one experiment worth of waste which is weighed and then the results shared to allow the E-factor to be calculated.

Mass intensity should be relatively easy to apply within an undergraduate laboratory session, providing that the weights of the reagents used are given on the practical script. In the case of recrystallisations *etc*, students would have to approximate how much solvent they have used and multiply this by the solvent density to give the weight. This is another metric that could be calculated outside of the practical session providing the students are aware of how much reagents and solvents that they have used to ensure that the result given is accurate.

Applying effective mass yield to undergraduate laboratory experiments should not cause any problems in terms of the practical aspect of the experiment, however, this metric requires the mass of the non-benign materials used in the reaction or process. For the students to use this metric, they must themselves decide which materials would be consider as non-benign, as already mentioned in the literature review, so far there is no agreed consensus as to what constitutes a non-benign material. If students are asked to fill out COSHH forms before their practical session, this metric could be used as the information on the form should give them guidance in order for them to decide whether or not the materials they are using are non-benign, this must also be related to the volume of the material that they are using.

Reaction mass efficiency would be simple to apply to an undergraduate experiment providing the weights of the original reactants and the desired product are known.

4.2.3.5 Judging 'greenness'

Looking at the results of the undergraduate practicals, it is obvious that there is no single metric that can be applied to them all to give an indication of how green the reaction is. These metrics are often contradictory to each other, an example of this is in the Preparation of Tetraiodotin(IV) from the elements. The crude yield showed a reasonably successful reaction at 72%, however the E-factor gave a result of 24.49 which indicated the production of a moderate amount of waste in relation to the amount of product. The atom economy signified that the reaction proceeded well as it was calculated as 100%, therefore this would be desired for an ideal green reaction. The mass intensity on the other hand signified that there was a large weight of reactants and auxiliaries used to form the product and was quite far from the target of 1 at 38.3, this is undesirable and would not be considered very green. The reaction mass efficiency was 88% which is desirable for a green reaction. This shows the need for a single metric that can be applied to give one number to assess how green the reaction is.

4.2.3.6 Summary

The green chemistry metrics applied to the undergraduate practicals showed that they were often contradictory and not applicable to all experiments. They also did not address issues such as chemical safety and energy use which were criteria that are considered important by students and employers involved in the needs analysis (see Chapters Two and Three) in terms of raising awareness of these issues. This has shown the need for a single metric tool to assess undergraduate practicals. Carrying out these experiments in the context of green chemistry and sustainability has identified areas for improvement such as reduction of reaction scale and reducing waste generation.

4.3 Developing a metric system

After assessing the metrics available it was obvious that there was no single one that can be applied simply to an undergraduate laboratory practical. The metrics tested are flawed in the sense that they were predominantly designed for organic synthesis assessment and as a result were not applicable to all practicals meaning that some could not be assessed. The use of green chemistry metrics also showed how it was not possible to judge how green an experiment was using these metrics as they did not always give a unanimous result, for example, one metric may suggest a green experiment, but another applied to the same experiment could suggest it was poor in terms of greenness. For these reasons a metric system was developed.

The aims of this metric system when applied to an undergraduate laboratory environment are:

- To provide a single tool that allows students to assess their practical work resulting in one single number of 'greenness' to allow the practical to be ranked on a scale. This should also allow easy comparison between practicals
- To combine environmental awareness and safety and encourage students to consider the hazards associated with the practical work that they undertake
- To allow students to identify problem areas of their practical, which may provide a point for discussion and the chance for students to suggest improvements

- To raise awareness of issues that may otherwise be overlooked and taken for granted such as power use
- To promote the twelve green principles of chemistry

The environmental assessment metric was based on and influenced by the EcoScale [87] system developed by Van Aken *et al*. In terms of an undergraduate laboratory, the EcoScale metric did not address all the areas that it was thought that students should be aware of, for example waste. As mentioned in Chapter One, Klinghirn describes how waste monitoring can raise awareness and allow students to think about how waste could impact on the environment if it were released. [8] Other areas such as awareness of the hazards of the chemicals used brought up by the feedback from both the students (see Chapter Two) and companies within industry are included.

The following criteria were chosen for the environmental assessment metric:

- Reaction efficiency
- Reaction waste
- Toxicology and safety
- Unit operations and energy consumption
- Resource consumption

Each criteria is divided further, for example; Reaction Efficiency contains, percentage yield, atom economy, carbon efficiency and the use of catalysts. A penalty point system is used for to score the criteria much like that seen in the EcoScale metric [87] and is scored out of 100. A score of 100 indicating a successful reaction and 0 indicating an unsuccessful reaction in terms of 'greenness'.

These criteria also contain some of the original metrics tested on the undergraduate practicals in order to familiarise the students with them in the case that they want to pursue careers in the chemical industry where some of them are currently being used.

This metric system incorporates some of the twelve green principles such as atom economy and the use of catalysts to draw further attention to them, promote their use within the undergraduate chemistry laboratory, and to ensure that students understand them and the implications of them. They also provide a focal point to centre questions around to encourage students to think around and deeper into issues surrounding green chemistry and sustainability.

4.3.1 Criteria for the metric system

The following shows how penalty points are scored for each area of the environmental assessment metric. When used as a tool for an undergraduate laboratory, students are not required to use formulae as spreadsheet is prepared for their use which just requires them to enter the data in the correct areas, to avoid any confusion, each section of the spreadsheet is signposted with information of how to fill in the table.

The following shows the environmental assessment table:

Environmental Impact Factor	Qualifying Criteria		Penalty	
REACTION EFFICIENCY	Percentage Yield	0	0	A
	Atom Economy	0	0	
	Carbon Efficiency	0	0	
	Catalysis	0	0	
REACTION WASTE	Non Hazardous Aqueous	0	1	
	Heavy Metal Aqueous	0	5	
	Halogenated Solvents	0	4	B
	Non-halogenated Solvents	0	2	
	Acid/Basic Aqueous	0	1	
	Non Hazardous Solids	0	1	
	Hazardous Solids	0	2	
CHEMICAL SAFETY	Harmful	0	2	
	Corrosive	0	2	
	Toxic to the Environment	0	3	C
	Toxic	0	3	
	Extremely Toxic	0	3	
	Irritant	0	2	
	Carcinogen	0	3	
	Mutagen	0	3	
	Oxidising	0	2	
	Flammable	0	2	
	Explosive	0	4	
	Teratogen	0	3	
UNIT OPERATIONS & ENERGY CONSUMPTION	Reflux (starfish)	0	1	
	Reflux (individual)	0	4	
	Distillation (waterbath)	0	4	
	Heating (waterbath)	0	3	D
	Heating (hotplate)	0	2	
	Stirring	0	2	
	Heating and stirring	0	3	
	Rotary Evaporation	0	5	
	Infrared	0	5	
RESOURCE CONSUMPTION	Water	0	4	E
	Reactants, solvents, catalysts	0	5	F
	Energy	0	5	G

Total Penalty **Final Score** (out of 100) %

Table 4.6 The metric system and penalty points

A = Students enter their calculated percentage yield, atom economy, carbon efficiency and use of catalyst calculation into this column which allows penalty points to be scored in the adjacent column.

B = The amount of waste is considered by the students and entered into this column, if they have generated less than 150 cm^3 of the specific waste they enter 1. If they have generated more than or equal to 150 cm^3 of the waste they enter 2. If they have not generated any of this waste they enter 0. The penalty points are then awarded by multiplying this number by the penalty associated with that type of waste.

C = Chemical hazards and safety are considered. Each chemical is associated with a particular penalty and this is multiplied by the number of chemicals (entered into this column) used within the experiment with that specific hazard.

D = Students are directed to enter whether they have used the specific piece of apparatus for less than thirty minutes (enter 1), more than or equal to thirty minutes (enter 2), or not at all (enter 0) this is then multiplied by the penalty points associated with this piece of apparatus.

E = Students are asked to consider the apparatus that they have used and the unit operations that they have carried out requiring the use of water. If they have used rotary evaporation (for more than 15 minutes), Distillation or Individual Reflux they are directed to enter 2. Rotary evaporation (for less than 15 minutes) or Starfish Reflux they are directed to enter 1. A water bath they are directed to enter 0.5. Students are also given an option to enter 2.5 if they believe that the water consumption for the experiment was excessive. The number entered is then multiplied by the penalty.

F = Students are asked to consider the scale that their reaction has been carried out on.- If they think the scale was appropriate for the work carried out they are directed to enter 0. If they think the scale could have been reduced slightly they are directed to enter 1 and if they believe that the scale should have been reduced further, they are directed to enter 2, this is then multiplied by the penalty points.

G = Students are asked to consider how much apparatus requiring power has been used during their experiment. If they have not used any apparatus requiring electricity they are directed to enter 0. If they have used up to and including two pieces of apparatus requiring electricity they are directed to enter 1. If they have used three or more pieces of apparatus requiring electricity they are directed to enter 2, which is then multiplied by the penalty points.

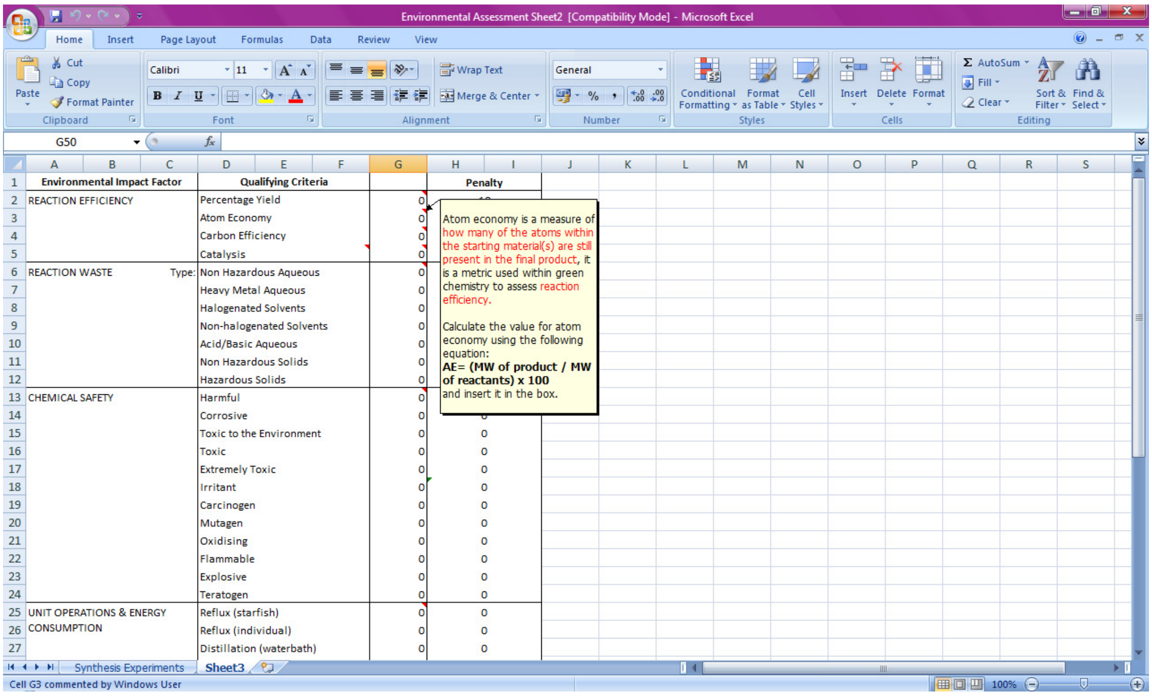


Figure 4.1 Screenshot showing an example of the metrics spreadsheet in Microsoft Excel

4.3.1.1 Reaction efficiency

Percentage yield

Reaction efficiency has traditionally been assessed using percentage yield. [13] Although this metric does not take environmental issues into consideration, it is still an important metric and should still be included within the environmental assessment. Indirectly this metric also gives a brief indication of how much of the original reactants have been used to form the final product, a high percentage yield indicating that a large amount of reactants has been used up, a low percentage yield indicating that a small amount has been used up with the remaining starting materials potentially ending up as waste. Higher yields can also result in an easier work up procedure as there are less side products to remove, therefore a potentially reducing the number of steps and materials required.

For this metric system the recovery yield after purification will be more practical to use and will avoid confusion when choosing which one to use. This should also be used as it is the product that remains after the reactions and processes are carried out and all factors that could affect the environment would be included within this time. If the experiment carried out by the students does not require purification, the crude yield is used. Simply, the remaining product after all transformations, processes and reactions is carried out.

Atom Economy and Carbon Efficiency

Atom economy is included in this metric as another method of assessing reaction efficiency. As already mentioned in the introduction to this chapter, it is considered as a green chemistry metric. Atom economy is calculated using the equation proposed by Trost [75] before entering it into the metric system, therefore fully familiarising students with this metric. Atom Economy is also present as one of the twelve green principles, and states that ‘synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product,’ [13] which also shows the importance of its inclusion within the metric system, this gives students a gauge of how many atoms in the original reactants remain in the final product which can then lead students to consider related issues. Carbon efficiency is regarded in the same way and calculated using the equation proposed by GlaxoSmithKline. [70]

The maximum penalty points awarded for percentage yield, atom economy and carbon efficiency is 10, to calculate the penalty the following is used:

Penalty points = (10 - (% calculated/10))

Equation 4.10 Calculating penalty points associated with percentage yield

The following shows this applied to the synthesis of acetylsalicylic acid:

The synthesis was performed using salicylic acid and acetic anhydride and yielded 75% of pure aspirin, to obtain a penalty score for the assessment, the percentage yield is entered into the formula:

Penalty points = (10 – (75/10)) = 2.5

This shows that a relatively good conversion took place and therefore was awarded a low number of penalty points. This same method is applied to atom economy and carbon efficiency.

Obviously a high yielding, high atom economical reaction is most desired, so a 100% percentage yield/atom economy/carbon efficiency would be awarded no penalty points and a low yielding reaction is scored penalty points accordingly.

The Use of Catalysts

One of the twelve green principles states how 'catalytic reagents' (as selective as possible) are superior to stoichiometric reagents. [13] Therefore the reaction efficiency section of the metric system includes the use of catalysts. This will draw attention to this area, which could otherwise be overlooked by a student and will allow them to look for the catalysts that are potentially used within their reaction. Even if catalysts are not used, this could still encourage them to consider the idea of catalysis and provide an opportunity for students to answer questions based around this topic such as the benefits of using catalysts and why.

In order to obtain a penalty score to enter into the metric system, the following equation is used:

Penalty points = (10 - ((No. of steps using a catalyst/No. of steps in the synthesis) x 10)

Equation 4.11 Calculating penalty points for the use of catalysts

4.3.1.2 Reaction Waste

Waste can often be something that is overlooked by students within a laboratory environment. To raise awareness of this issue the metric system requires students to monitor and measure how much and which type of waste is being generated.

The waste is classified into the following categories:

- Non Hazardous Aqueous
- Heavy Metal Aqueous
- Halogenated Solvents
- Non-halogenated Solvents
- Acidic/Basic Aqueous
- Non Hazardous Solids
- Hazardous Solids

Students are required to record the type and approximate amount of waste that they generate as they go along, which will bring further attention to it. To use this within the metric system each type of waste has a penalty associated with it weighted by the cost and ease of disposal and therefore its toxicity. For example, heavy metal aqueous waste will have a much higher penalty associated with it than non hazardous aqueous waste.

This may also allow students to consider the effect that the waste they are generating may have on the environment and the correct way to deal with this waste. This part of the metric centres again around the twelve green principles: It is better to prevent waste than to treat or clean up waste after it has been created.

4.3.1.3 Toxicology and Safety

Human and environmental safety is vital within any laboratory, not just an undergraduate setting. A result of the work carried out on student perceptions was that they were often not aware of the hazards associated with the chemicals that they use during their practical sessions. This part of the metric system will require students to seek information relating to the hazards of the chemicals that they are using by using MSDS or databases and the hazard symbols that these sources give. The following hazards are included within the metric system:

- Harmful
- Corrosive
- Toxic to the Environment
- Toxic
- Extremely Toxic
- Irritant
- Carcinogen
- Mutagen
- Oxidising
- Flammable
- Explosive
- Teratogen

This scoring is based on that proposed by the EcoScale, [87] and to avoid complex calculations, which is highly desired for integration into an undergraduate laboratory environment in order not to discourage the students from using it, each hazard is associated with a penalty which is multiplied by the number of chemicals possessing this hazard. The focus on this area can encourage students to consider alternative reagents and solvents with less hazards but which still deliver the same chemical effects which again promotes more of the twelve principles of green chemistry: Inherently Safer Chemistry for Accident Prevention- substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires and Less Hazardous Chemical Syntheses- wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment. [13]

4.3.1.4 Energy Consumption

The metric system considers the energy consumption associated with unit operations that are common within the undergraduate laboratory. For the purposes of simplicity this section is scored on the time that a certain piece of equipment is used or unit operation is carried out. The following unit operations are considered:

- Reflux (starfish)
- Reflux (individual)
- Distillation
- Heating (waterbath)
- Heating (hotplate)
- Mechanical stirring
- Heating and stirring
- Rotary evaporation
- Infrared spectroscopy analysis

Each unit operation is scored according to how much power it uses, for example, a reflux carried out on a starfish is less demanding energy wise as several reflux may be carried out at one time, therefore this will mean that this unit operation would be scored with a lower penalty than that of an individual set up. The student will then enter whether they have used this for more or less than thirty minutes or not at all. This time scale was chosen as unit operations within an undergraduate laboratory are often carried out in relatively short periods of time, so this allows them to be captured.

This section is also associated with one of the twelve green principles: Design for Energy Efficiency- energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure. [13]

4.3.1.5 Resource Consumption

To draw attention to the resource consumption, water, energy and chemicals used to complete the reaction are considered. In an undergraduate laboratory environment, these criteria are rarely taken into account.

Water consumption

The water consumption part of the metric system requires students to consider how much water they have used. Unit operations such as distillation or individual reflux encounter higher penalty points than a starfish reflux as they use more water per individual experiment. Students also have the option to show water consumption as excessive if they feel that it is necessary, this will have a ten point penalty.

Reactants, solvents, catalysts

The use of solvents, reactants and catalysts is measured simply by considering the scale at which the reaction is carried out. Students must decide whether or not they believe that the scale is appropriate for the work that they are carrying out or whether it could be reduced slightly/dramatically. Using scale as the basis to assess the usage of reactants, solvents and catalysts allows this area of the metric system relatively simple.

Energy

To draw attention to the energy consumption throughout the entire chemistry practical rather than for each unit operation, the energy is assessed by considering the number of unit operations that have required the use of electricity. To keep this calculation simple, students will enter into the metric whether they have used two or less, three or more or no pieces of apparatus requiring power.

4.3.2 Adapting the metric system

After the preliminary work testing the green chemistry metrics in the literature, it became apparent that for them to be applicable to the reactions carried out, they required a measureable product. This meant that these metrics would not be applicable to practicals such as those within physical and some inorganic chemistry. This was part of the reason for the development of a new metric system.

When developing the metric system, it was thought that the metrics such as percentage yield, atom economy, carbon efficiency and mass intensity should still be included as these would give students knowledge of their existence, therefore if they were to seek employment within the chemical industry, they would have some experience of their use. As already mentioned, these are not applicable to all forms of chemistry; however, the reaction efficiency stage of the metric system can be discounted when carrying out practicals such as titration *etc,* with a final percentage score calculated out of 60.

In the design stages of this metric system, each section was scored out of ten with penalties taken from this. An average out of ten of the criteria was taken, however when testing the metric, it was found that those sections that did not encounter any penalty points still allowed a 'bad' reaction in terms of green chemistry and sustainability due to the use of high amounts of hazardous chemicals *etc* to be awarded a high score. For this reason, the approach taken using an average to calculate the overall score was replaced by taking penalty points from a beginning score of 100, resulting in a percentage.

4.3.3 Testing the metric system

The semi-quantitative metric system was tested by applying it to selected undergraduate practicals. This was to determine how well this new system works in relation to the undergraduate practicals, its ease of use and if any areas of the system could be improved.

Application to the synthesis of acetylsalicylic acid

The synthesis of acetylsalicylic acid is carried out using salicylic acid and acetic anhydride, in the presence of a sulphuric acid catalyst. The practical uses heating from a water bath and does not require any additional apparatus requiring power, the acetylsalicylic acid is then recrystallised from water. Chemical hazards were obtained from MSDS provided by Sigma Aldrich.

The following shows the assessment for this experiment:

Environmental Impact Factor	Qualifying Criteria		Penalty
REACTION EFFICIENCY	Percentage Yield	75	2.5
	Atom Economy	75	2.5
	Carbon Efficiency	82	1.8
	Catalysis	1	0
REACTION WASTE	Non Hazardous Aqueous	1	1
	Heavy Metal Aqueous	0	0
	Halogenated Solvents	0	0
	Non-halogenated Solvents	0	0
	Acid/Basic Aqueous	0	0
	Non Hazardous Solids	0	0
	Hazardous Solids	0	0
CHEMICAL SAFETY	Harmful	2	4
	Corrosive	2	4
	Toxic to the Environment	0	0
	Toxic	0	0
	Extremely Toxic	0	0
	Irritant	1	2
	Carcinogen	0	0
	Mutagen	0	0
	Oxidising	0	0
	Flammable	2	4
	Explosive	0	0
	Teratogen	0	0
UNIT OPERATIONS & ENERGY CONSUMPTION	Reflux (starfish)	0	0
	Reflux (individual)	0	0
	Distillation (waterbath)	0	0
	Heating (waterbath)	2	6
	Heating (hotplate)	0	0
	Stirring	0	0
	Heating and stirring	0	0
	Rotary Evaporation	0	0
	Infrared	0	0
RESOURCE CONSUMPTION	Water	0.5	2
	Reactants, solvents, catalysts	1	5
	Energy	1	5

Total Penalty 39.8 **Final Score** (out of 100) 60.2%

Table 4.7 The metric system applied to the synthesis of acetylsalicylic acid

The synthesis of acetylsalicylic acid from acetic anhydride and salicylic acid encountered a penalty point score of 39.8 which gave a final score of 60.2%. This shows a relatively good reaction in terms of green chemistry and sustainability. Low penalty scores were awarded within the reaction efficiency stage due to a high conversion and use of catalyst. Reaction waste also encountered a low score due to the generation of non-hazardous aqueous waste which is relatively easy to dispose of. As only one piece of apparatus requiring energy (water bath) was used, the penalty points within the unit operation and energy consumption section were also low. The use of a water bath did not require much in terms of water consumption and therefore was scored accordingly. The scale of the reaction was thought of as being able to be decreased slightly and hence suffered a small penalty.

Preparation of tetraiodotin(IV): Preparation from the elements

Tetraiodotin(IV) is prepared from sheet tin and iodine in acetic acid and acetic anhydride. The reaction mixture is refluxed on a water bath until all or most of the tin metal has been consumed by the reaction, it is then filtered from the reaction mixture.

The following shows the assessment for this experiment:

Environmental Impact Factor	Qualifying Criteria		Penalty
REACTION EFFICIENCY	Percentage Yield	76	2.4
	Atom Economy	100	0
	Catalysis	0	10
REACTION WASTE	Non Hazardous Aqueous	0	0
	Heavy Metal Aqueous	0	0
	Halogenated Solvents	1	4
	Non-halogenated Solvents	1	2
	Acid/Basic Aqueous	0	0
	Non Hazardous Solids	0	0
	Hazardous Solids	0	0
CHEMICAL SAFETY	Harmful	3	6
	Corrosive	2	4
	Toxic to the Environment	1	3
	Toxic	0	0
	Extremely Toxic	0	0
	Irritant	0	0
	Carcinogen	1	3
	Mutagen	0	0
	Oxidising	0	0
	Flammable	2	4
	Explosive	0	0
	Teratogen	0	0
UNIT OPERATIONS & ENERGY CONSUMPTION	Reflux (starfish)	0	0
	Reflux (individual)	2	8
	Distillation (waterbath)	0	0
	Heating (waterbath)	0	0
	Heating (hotplate)	0	0
	Stirring	0	0
	Heating and stirring	0	0
	Rotary Evaporation	0	0
	Infrared	0	0
RESOURCE CONSUMPTION	Water	2	8
	Reactants, solvents, catalysts	1	5
	Energy	1	5

Total Penalty 64.4 **Final Score** (% out of 90) 39.6%

Table 4.8 The metric system applied to the preparation of tetraiodotin(IV)

The preparation of tetraiodotin(IV) from the elements was given a total penalty of 64.4 which resulted in a final score of 39.6% which showed a relatively poor reaction in terms of green chemistry and sustainability in comparison to the assessment of the synthesis of aspirin.

The penalty points were mostly scored due to the generation of halogenated and non-halogenated solvent waste and the use of chemicals with hazards such as carcinogen and toxic to the environment which are awarded higher penalty points. The use of individual reflux also encountered a higher penalty due to the water and energy consumption.

4.3.4 Summary of metric system

Much like the EcoScale system, this metric presented is a semi-quantitative tool that can be used to assess undergraduate chemistry practicals. The metric system is not limited to a specific branch of chemistry as it can be manipulated to include all. In the past, metrics have mostly been associated with organic chemistry and the efficiency of these reactions; however, this metric goes beyond this to include issues associated with the majority of practicals such as waste, chemical hazards, energy associated with unit operations and resource consumption. One of the main aims of this metric system is to raise awareness of these issues that are associated with green chemistry and sustainability which with use should be achieved as it highlights areas that traditional chemistry practicals may not be considered.

The scoring system is relatively easy to use and using it within a pre-prepared spreadsheet with pointers to direct students in the right way, allows students to input their data quickly to give them a result that can be compared other experiments and the percentage score gives them an indication of how well their reaction has performed.

This metric system takes into account some of the twelve principles of green chemistry which provides an extra vehicle for the promotion of them and to encourage students to recognise them as being an integral part of chemistry. It can also act as a talking and discussion point to centre questions around regarding how reactions may be improved *etc*.

CHAPTER FIVE: Conclusions

5.0 Conclusions and further work

The aim of this work was to provide a starting point to inform curriculum development for integrating sustainability and environmental responsibility into the existing chemistry curriculum at the University of Bradford. This project has addressed areas of best practice for integrating these concepts, the needs of current students, staff and potential future employers and the application of green chemistry metrics to undergraduate practical modules which led to the design of a semi-quantitative environmental assessment metric.

A number of ways to integrate sustainability and environmental responsibility into the curriculum were identified, such as substituting experiments for greener ones, applying green chemistry metrics, utilising the twelve green principles and the use of pre and post lab questions covering this material. This project has taken the metrics route.

The needs of students and staff at the University of Bradford were explored. These small scale research studies showed a great deal of positivity towards the idea of integrating sustainability and environmental awareness into the curriculum. Companies spoken to expressed how students understanding these issues would have benefits to them.

Green chemistry metrics were found to often contradict each other when applied to the same experiment and were not always applicable to all forms of experiment. For this reason a prototype semi-quantitative environmental assessment metric has been designed which incorporates chosen green chemistry metrics to familiarise students with them due to the use of them within the chemical industry. Issues such as waste generation and chemical safety are addressed in order to raise awareness and prevent students from overlooking these issues, and the twelve green principles are promoted through the chosen criteria for assessment providing opportunities for discussion points. In order to make this system fully quantitative, further work concerning power and water usage must be carried out. Power and water meters may be used by students to assess the exact amount of power and water that they are consuming through carrying out their reaction and the metric system may be suitably adapted in order to allow students to input this data.

6.0 References

1. P. T. Anastas and J. B. Zimmerman, *Environmental Science and Technology*, 2003, **37**, 94-101.
2. H. v. Weenen, *International Journal of Sustainability in Higher Education*, 2000, **1**, 20-34.
3. The Brudtland Commision., *Our Common Future*, Oxford University Press, New York, 1987.
4. J. Pope, D. Annandale and A. Morrison-Saunders, *Environmental Impact Assessment Review*, 2004, **24**, 595-616.
5. *Report of the World Commision on Education and Development*. http://www.un-documents.net/wced-ocf.htm, 1987, accessed: 4th March 2010.
6. J. H. Clark and D. J. Macquarrie, *Handbook of green chemistry and technology*, Blackwell Science, Oxford, 2002.
7. A. v. Roon, H. A. J. Govers, J. R. Parsons and H. V. Weenen, *International Journal of Sustainability in Higher Education*, 2001, **2**, 161-179.
8. P. T. Anastas, I. J. Levy and K. E. Parent, eds., *Green chemistry education : changing the course of chemistry*, American Chemical Society, Washington, DC, 2009.
9. R. A. Sheldon, *Journal of Environmental Monitoring*, 2008, **10**, 406–407.
10. P. T. Anastas and M. M. Kirchoff, *Accounts Chem Res*, 2002, **35**, 686-694.
11. D. L. Hjeresen, D. L. Schutt and J. M. Boese, *Journal of Chemical Education*, 2000, **77**, 1543.
12. B. Braun, R. Charney, A. Clarens, J. Farrugia, C. Kitchens, C. Lisowski, D. Naistat and A. O'Neil, *Journal of Chemical Education*, 2006, **83**, 1126-1129.
13. P. T. Anastas and J. C. Warner, *Green chemistry : theory and practice*, Oxford University Press, Oxford, 1998.
14. J. H. Clark, *Green Chem*, 2006, **8**, 17-21.
15. J. H. Clark, *Green Chem*, 1999, **1,** 17-21.
16. Uctas, R. *Chemical industry struggles with public image*, http://www.icis.com/Articles/2007/09/17/9062166/chemical-industry-struggles-with-public-image.html, 2007, accessed 10th September 2010.
17. http://www.cefic.org/files/Publications/Scenarios2.pdf, 2007, accessed: 27th August 2010.
18. J. H. Clark, *Green Chem*, 1999, 1-8.
19. R. M. Downs and D. Stea, *Image and environment : cognitive mapping and spatial behavior*, Aldine Pub. Co, Chicago, 1973.
20. A. v. Roon, H. A. J. Govers, J. R. Parsons and H. v. Weenen, *International Journal of Sustainability in Higher Education*, 2001, **2**, 161-179.
21. Cognis.
22. T. Posner, *Review of European Community and International Environmental Law*, 1995, **4**, 164-167.
23. Health and Safety Executive, *The Restriction, Evaluation, Authorisation of Chemicals (REACH)*, http://www.hse.gov.uk/reach/, 2007, accessed: 6th March 2010.

24. Morson, K., *REACH and the move towards green chemistry*, http://www.stratfor.com/reach_and_move_toward_green_chemistry?fn=192397250, 2007, accessed: 8th September, 2010
25. Department for Business Innovation and Skills, *The Restriction of Hazardous Substances,* http://www.rohs.gov.uk/, 2005, accessed: 6th March 2010.
26. The Royal Society of Chemistry, *Statistics of Chemistry Education*, http://www.rsc.org/Education/Statistics/, 2010, accessed: 20th March 2010.
27. United Nations Statistics Division, *Environmental Statistics*, http://unstats.un.org/unsd/ENVIRONMENT/hazardous.htm, 2010, accessed: 2nd April 2010.
28. G. J. Miller, S. A. Heideman and T. J. Greenbowe, *Journal of Chemical Education*, 2000, **77**, 1185-1187.
29. A. Stark, D. Ott, D. Kralisch, G. Kreisel and B. Ondruschka, *Journal of Chemical Education*, 2010, **87**, 196-202.
30. M. C. Cann, *Greening Across the Chemistry Curriculum* http://academic.scranton.edu/faculty/cannm1/dreyfusmodules.html, 2000, accessed: 9th November 2009.
31. Green Chemistry Network, *Higher Education: Practicals in Green Chemistry,* http://www.greenchemistrynetwork.org/higher-education.htm, 2009, accessed: 9th November 2009.
32. The University of Oregon Green Chemistry Department, *Greener Education Materials for Chemists,* http://greenchem.uoregon.edu/gems.html, 2004, accessed: 22nd October 2009.
33. H. W. Roesky and D. K. Kennepohl, *Experiments in green and sustainable chemistry*, Wiley-VCH, Weinheim, 2009.
34. M. M. Singh, Z. Szafran and R. M. Pike, *Journal of Chemical Education*, 1999, **76**, 1684.
35. M. Abdullah, N. Mohamed and Z. H. Ismail, *Journal of Science and Mathematics Education*, 2007, **30** 44-72.
36. LabRATS Initiative University of California: Santa Barbra, *UCSB Sustainability: Laboratory Research And Technical Staff: LabRATS*, http://sustainability.ucsb.edu/LARS/, 2007, accessed: 4th March 2010.
37. The Higher Education Academy, *Sustainable development in higher education : current practice and future developments : a progress report for senior managers in higher education.*, York, 2006.
38. A. L. Strauss and J. M. Corbin, *Basics of qualitative research : techniques and procedures for developing grounded theory*, 2nd edn., Sage, Thousand Oaks, Calif. ; London, 1998.
39. N. K. Denzin, *The research act: A theoretical introduction to sociological methods*, Aldine, Chicago, 1970.
40. D. T. Campbell and D. W. Fiske, *Psychological Bulletin*, 1959, **56**, 81-105.
41. UNESCO, *Education for Sustainable Development*, http://www.unesco.org/en/esd/, 1995, accessed: 18th October 2009.
42. D. E. Gray, *Doing research in the real world*, 2nd edn., SAGE, London, 2009.
43. W. E. C. Gillham, *Case study research methods*, Continuum, London, 2000.
44. D. Katz and R. L. Kahn, *The social psychology of organizations*, Wiley, New York, 1966.

45. M. Saunders, P. Lewis and A. Thornhill, *Research methods for business students*, 4th edn., FT/Prentice Hall, Harlow, 2007.
46. F. J. Smith, *Research methods in pharmacy practice*, Pharmaceutical Press, London, 2002.
47. S. B. Merriam, J. Johnson-Bailey, M. Lee, G. Ntseane and M. Muhamad, *International Journal of Lifelong Education*, 2001 **20**, 405-416.
48. T. Hall, *International Journal of Social Research Methodology*, 2000, **3**, 121-133.
49. C. A. Bailey, *A Guide to Field Research*, Pine Forge Press., Thousand Oaks California, 1996
50. J. P. Spradley, *Participant observation*, Thompson Learning, New York; London (etc.)), 1980.
51. W. E. C. Gillham, *Developing a questionnaire*, Continuum, London, 2000.
52. P. Munn and E. Drever, *Using questionnaires in small scale research: a beginner's guide*, SCRE Publications, Glasgow, 2007.
53. D. A. Dillman, *Mail and Internet Surveys: The tailored design method*, 2nd edn., John Wiley, Chicester 2007.
54. Fisher Scientific, *Introduction to Green Chemistry*, http://www.fishersci.com/wps/downloads/segment/ScienceEducation/pdf/green_IntroGreenChem.pdf, accessed: 18th October 2009.
55. T. M. Caro, R. Roper, M. Young and G. R. Dank, *Behaviour*, 1979, **69**, 303-315.
56. E. Latvala, P. Vuokila-Oikkonen and S. Janhonen, *Journal of Advanced Nursing*, 2000, **1**, 1252-1257.
57. N. Moore, *How to do research: a practical guide to designing and managing research projects*, 3rd edn., Facet Publishing, London, 2006.
58. L. Templeton, A. Deehan, C. Taylor, C. Drummond and J. Strang, *British Journal of General Practice*, 1997, **47**, 91-94.
59. C. Robson, *Real world research : a resource for social scientists and practitioner-researchers*, 2nd edn., Blackwell, Oxford, 2002.
60. S. Lensing, Y., S. R. Gillapsy, P. M. Simpson and S. M. Jones, *Evaluation and the Health Professions*, 2000 **23**, 348-359.
61. R. E. Boyatzis, *Transforming qualitative information: thematic analysis and code development.* , SAGE Publications, London, 1998.
62. V. Braun and V. Clarke, *Qualitative Research in Psychology*, 2006, **3**, 77-101.
63. The Royal Society of Chemistry, *Employer Categories for Chemistry Graduates*, http://www.rsc.org/images/EmployerCategoriesChemistryGraduates_tcm18-94254.pdf, accessed: 6th June 2010.
64. JISC Digital Media, *Recording Telephone Conversations*, http://www.jiscdigitalmedia.ac.uk/audio/advice/recording-telephone-conversations/, 2010, accessed: 8th June 2010.
65. M. Stacey, *Methods of social research*, Pergamon, Oxford, 1969.
66. B. Somekh and C. Lewin, *Research methods in the social sciences*, SAGE, London, 2005.
67. J. Zeisel, *Inquiry by Design: Tools for Environment-Behaviour Research*, Cambridge University Press, Cambridge, 1984.
68. W. E. C. Gillham, *The research interview*, Continuum, London, 2000.

69. D. Armstrong and M. Ashworth, *British Journal of General Practice*, 2000, **50**, 479-480.
70. D. J. C. Constable, A. D. Curzons and V. L. Cunningham, *Green Chem*, 2002, **4**, 521-527.
71. J. Andraos, *Organic Process Research and Development*, 2005, **9**, 149-163.
72. R. Henderson, 2007, vol. 2010.
73. A. D. Curzons, D. J. C. Constable, D. N. Mortimer and V. L. Cunningham, *Green Chem*, 2001, **3**, 1-6.
74. A. E. Marteel, J. A. Davies, W. O. Olson and M. A. Abraham, *Annual Reviews Environmental Resources* 2003, **28**, 401-428.
75. B. M. Trost, *Science*, 1991, **254**, 1471-1477.
76. B. M. Trost, *Accounts Chem Res*, 2002, **35**, 695-705.
77. B. M. Trost, *Chem. Int. Ed. Engl*, 1995, **34**, 259.
78. R. A. Sheldon, *Chem. Tech.*, 1994, **24**, 38-47.
79. N. G. Anderson, *Practical Process Research and Development*, Academic Press, San Diego, 2000.
80. A. S. Matlack, *Introduction to green chemistry*, Marcel Dekker, New York, 2001.
81. M. Lancaster, *Green chemistry : an introductory text*, Royal Society of Chemistry, Cambridge, 2002.
82. R. A. Sheldon, *Chem Commun*, 2008, 3352-3365.
83. A. Lapkin and D. Constable, *Green chemistry metrics : measuring and monitoring sustainable processes*, Wiley-Blackwell, Ames, Iowa, 2009.
84. R. A. Sheldon, *Precision process technology*, Amsterdam, 1993.
85. R. A. Sheldon, *Green Chem*, 2007, **9**, 1261–1284.
86. M. Eissen, K. Hungerbühler, S. Dirks and J. Metzger, *Green Chem*, 2003, **5**, 25-27.
87. K. Van Aken, L. Strekowski and L. Patiny, *Beilstein J Org Chem*, 2006, **2**.
88. R., A., Sheldon, *Consider the Environmental Quotient*, http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=7109196, 2009, accessed: 3rd June 2010.
89. T. Hudlicky, D. A. Frey, L. Koroniak, C. D. Claeboe and L. E. Brammer, *Green Chem*, 1999, **1**, 57-59.
90. J. Auge, *Green Chem*, 2008, **10**, 225-331.
91. R. A. Sheldon, *Chem Ind*, 1992, **1992**, 903.
92. D. Mayo, R. M. Pike and P. K. Trumper, *Microscale Techniques for the Organic Laboratory*, 3rd Ed. edn., Wiley and Sons, New York, 2009.